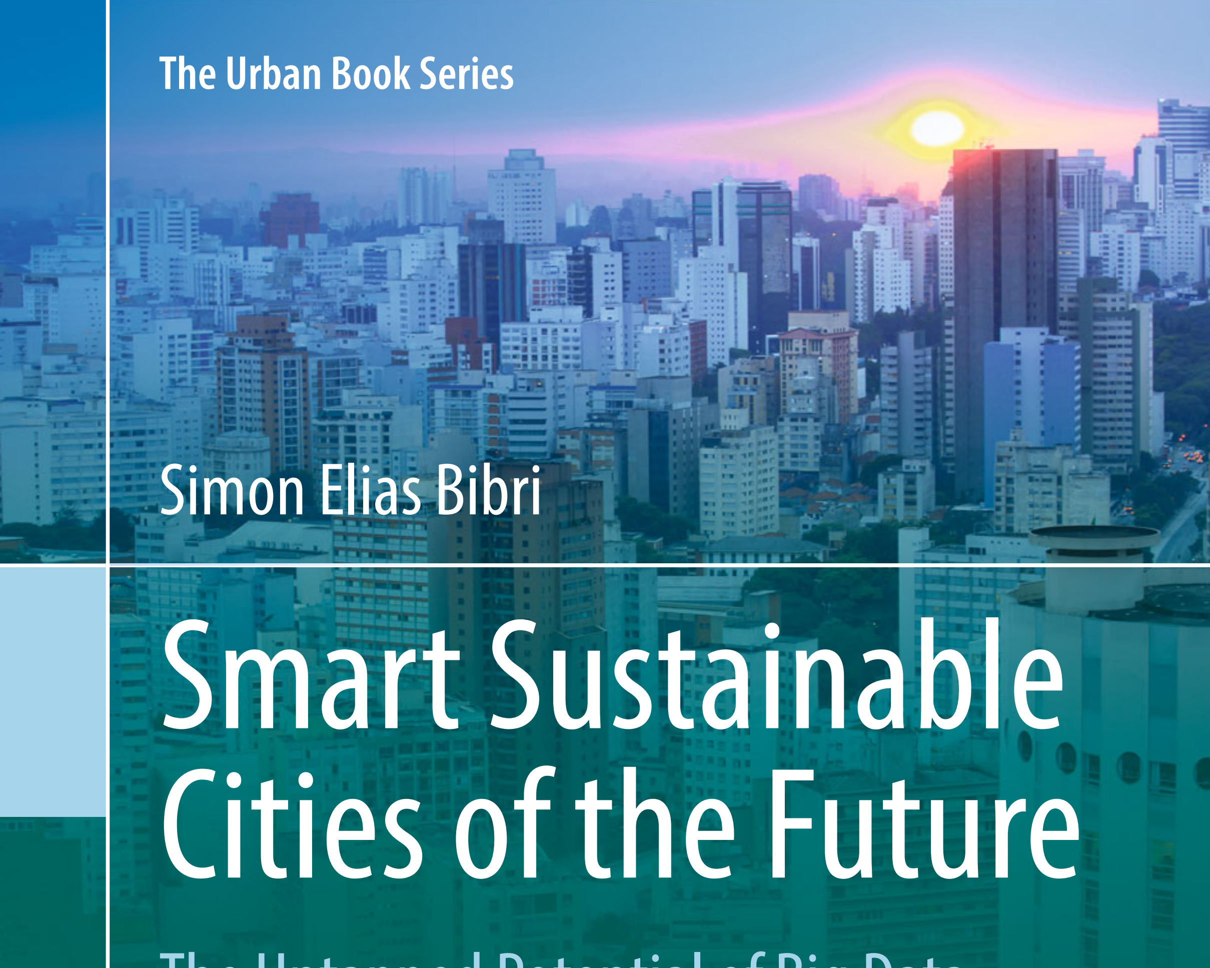

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Simon Elias Bibri

Smart Sustainable Cities of the Future

The Untapped Potential of Big Data Analytics and Context-Aware Computing for Advancing Sustainability

Springer

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The entire effort of your mind, soul, and heart working incessantly and in tandem, coupled wth your grit and perseverance, is what it takes to succeed in your intellectual endeavors. But to sustain momentum for the long haul or to cope with unforeseen circumstances as part of life sometimes necessitates special people to come along at the right time.

To my beloved sister, Amina, for her wholehearted love, immeasurable moral support, and unfailing encouragement; and to whom I owe my life for the sacrifice she has made for me, as well as for her willingness and determination to sacrifice a lot more so that I can continue to thrive in my academic endeavors and thus nourish my passion for the pursuit of knowledge.

To Prof. Bjørn Olav Åsvold—the most humanly generous and thoughtful person I have ever been so lucky as to have known—whom I hold in highest regard in respect of *his authentic moral fiber, genuine humbleness, and matchless empathy, and to whom I am deeply indebted for his immense help, incredible kindness, insightful advice, and approachability. I stand in awe of him.*

Preface

> It is a profoundly erroneous truism…that we should cultivate the habit of thinking what we are doing. The precise opposite is the case. Civilization advances by extending the number of important operations, which we can perform without thinking about them.
>
> —Alfred Whitehead

With new scientific discoveries and technological innovations, most notably big data analytics and context-aware computing as powerful drivers for the next wave of urban analytics and planning, we hope to fulfill Alfred Whitehead's maxim of achieving progress through the increasing automation and intelligence of solutions for overcoming the challenges of sustainability and urbanization in the context of smart sustainable cities of the future. To put it differently, noteworthy advances in data science, computer science, and complexity science and the related technologies and their novel applications inevitably bring with them wide-ranging common visions on how cities as social fabrics epitomizing the microcosm of the world in terms of encapsulating in miniature its characteristic features as to environmental change, economic development, and social transformation will evolve in the future. They moreover open entirely new windows of opportunity for the application of engineering- and computing- inspired solutions to once intractable and wicked urban problems. This relates to the role of science-based technology in modern society in terms of advancing almost all human endeavors and activities. More importantly, the primary goal of the construction of the techno-urban vision of smart sustainable cities is to provoke thought and discussion, to create fertile insights, to generate new opportunities, to depict possible futures, and crucially, to align key stakeholders and mobilize resources into the same direction.

Key Aims and Major Themes

This scholarly book has been written as a timely and comprehensive reference for several classes of readers who are interested in the interplay between computing, ICT, sustainable development, sustainability science, urbanization, and urban design and planning. It is therefore intended to help to explore the field of smart sustainable cities in its complexity, heterogeneity, and breadth, the many faces of a topical subject that is of major importance for the future, and that encompasses so much of modern urban life in an increasingly technologized, computerized, and urbanized world. Indeed, sustainable urban development is currently at the centre of debate in light of several ICT visions becoming concurrently achievable and deployable computing paradigms, and shaping the way cities will evolve in the future and tackle complex challenges with support of advanced technologies. Widely acknowledged as the most influential and enticing strands of contemporary computing and ICT, big data analytics and context-aware computing are certainly reshaping and enriching our experiences of how cities can function and be managed, planned, and developed. They are offering many new and unique opportunities for more informed and strategic decision-making with respect to our knowledge of how fast and best to address the challenges of sustainability and urbanization that are facing major cities of the world, and that will continue to grow in the years ahead. Therefore, there is a wide recognition and much enthusiasm about the immense possibilities created by new and more extensive sources of urban data to effectively monitor, understand, analyze, and plan cities to strategically improve their contribution to the goals of sustainable development through such processes as automation, optimization, control, management, strategy development, and policy design.

The primary goal of this book is to help readers view the challenges of sustainability and urbanization in the context of smart sustainable cities of the future from the perspective of big data analytics and context-aware computing. It is also to understand the fundamental principles of extracting useful knowledge and inferring context knowledge from large masses of data for enhanced decision-making and insights pertaining to urban operational functioning, management, planning, and development for the purpose of addressing those challenges. This book involves innovative computer-based and data-analytic research on smart sustainable cities as complex and dynamic systems. It provides theoretical and applied contributions fostering a better understanding and development of such systems and the synergistic relationships between the underlying physical and informational landscapes. It offers contributions pertaining to the ongoing development of computer-based and data science technologies for the processing, analysis, management, modeling, and simulation of urban data and the associated application in the operating and organizing processes of urban life—urban systems—that will advance different aspects of sustainability and contain the multidimensional effects of urbanization. Accordingly, this book focuses on city-related disciplines and sciences in relation to big data and context-aware technologies and their novel applications. In this respect, I give special importance to the general principles of such disciplines and sciences in terms of how computer science and data science are reshaping them and facilitating their amalgamation in the context of sustainability thanks to recent discoveries in urban analytics and computing—that make it possible to acquire a better understanding of urban systems and to enable an effective coordination of urban domains, coupled with the breakthroughs at the level of the core enabling technologies underlying big data analytics and context-aware computing. These include sensing technologies, data processing platforms, middleware architectures, cloud and fog computing infrastructures, and wireless communication networks. Such discoveries and breakthroughs are making it increasingly possible to build novel systems based on that understanding and coordination for the purpose of strategically advancing the contribution of smart (and) sustainable cities to the goals of sustainable development.

To facilitate embarking on exploring the realm of smart sustainable cities of the future, I have designed this book around three related aims: to help readers gain essential underpinning knowledge about the topic of smart sustainable cities; to help them develop a deeper understanding of this emerging techno-urban phenomenon as they make connections between their own understandings of smart and sustainable cities and emerging theoretical, analytical, and applied concepts; and, more importantly, to encourage them to take part in the ongoing debate about smart sustainable urban development. This is indeed gaining special importance in, and whose prominence will increase throughout, the twenty-first century, as cities across the globe are increasingly facing intractable and wicked problems due to the imminent challenges of sustainability and urbanization.

Subject Treatment and What Makes the Book Unique in its Field

This book is the first of its kind with respect to the approach into probing the new techno-urban phenomenon and flourishing field of smart sustainable cities—based on a uniquely holistic and interdisciplinary perspective. In response to the growing need for an inclusive analysis or a multi-perspectival approach to the study of the phenomenon of smart sustainable cities, this book deals with the interdisciplinary aspects of the rapidly evolving field of smart sustainable urban planning and development in the context of technologically and ecologically advanced nations. This field is still in its early stages and the subject matter draws upon a set of influential theories and powerful discourses with practical applications—i.e. the application of urban design and planning, sustainable development, sustainability science, computer science, data science, and ICT as a foundation for future urban practices. In view of that, this book adopts a unique and compelling approach to cross-disciplinary integration entailing a variety of theoretical, applied, scientific, and technological perspectives drawn from computer science, data science, complexity sciences, ICT, socio-technical studies, environmental sciences, innovation science, urban studies, policy, philosophy, ecology, and sociology. This is meant to achieve a broader understanding of the multifaceted phenomenon of smart sustainable cities, and also constitutes a means to facilitate collaboration among and between an array of academic and scientific disciplines for the primary purpose of generating the kind of interactional knowledge necessary for a more integrated perspective on the topic of smart sustainable cities. This is a core contribution that supports the foundational ethos of interdisciplinarity associated with the blossoming field of smart sustainable urban planning and development.

In specific terms, the focus in this book is on exploring the potential of ICT of the new wave of computing to provide the technological infrastructures, solutions, and approaches necessary for advancing the contribution of sustainable urban forms to the goals of sustainable development based on an effective integration of the design and planning concepts and principles of such forms with big data analytics and context-aware computing in terms of the underlying core enabling technologies and their novel applications and services being offered by smart and smarter cities. While big data analytics and context-aware computing play a crucial role for smart sustainable cities, it is worth pointing out that other ICT potentials (robotics, cybernetics, etc.) also have a role to play in this regard. However, the use of big data analytics and context-aware computing as prerequisite technologies for realizing ICT of the new wave of computing entails that smart sustainable cities will take the form of constellations of instruments—architectures, platforms, applications, and computational and data analytics capabilities across many spatial scales that are connected through wirelessly ad hoc and mobile networks with a modicum of intelligence. These networks can provide and coordinate continuous data on different features of urban domains (activities, processes, structures, citizens, and entities) in terms of the flow of decisions about the physical, infrastructural, operational, functional, and socioeconomic forms of smart sustainable cities. This constitutes a fertile environment conducive to monitoring, understanding, analyzing, operating, managing, and planning smart sustainable cities. This is about leveraging their informational landscape in addressing the challenges of sustainability and urbanization. One of the salient driving factors for urban design and planning embracing the wave of smartness lies in the immense opportunities being created through the utilization of the innovative solutions and sophisticated methods increasingly enabled by big data and context-aware technologies that are being designed and applied for supporting the goals of sustainable development. In all, this book offers a novel, fresh, and all-encompassing approach to the exploration of smart sustainable cities as an integrated and holistic urban development strategy. In doing so, it combines academic, scientific, and practical relevance with urban, technological, social, and environmental analysis, supported with critical and reflective thinking.

Originality and Value

Up till now, no comprehensive book has, to the best of one's knowledge, been produced elsewhere—as to systematically exploring the field of smart sustainable cities in terms of seamlessly amalgamating the design and planning principles of sustainable urban forms with the novel applications of ICT of the new wave of computing for urban sustainability, i.e. merging the physical and informational landscapes of smart sustainable cities in ways that strategically assess, improve, and sustain their contribution to the goals of sustainable development. Nor has any book approached the topic from the perspective of integrating data science, computer science, complexity science, and the social sciences—more specifically, the untapped potential of big data analytics and context-aware computing for overcoming the imminent challenges of sustainability and urbanization in the context of smart sustainable cities as complex systems. In this regard, this book combines big data and context-aware technologies and their novel applications for the sheer purpose of harnessing and leveraging the disruptive and synergetic effects of ICT on modern cities in the needed transition towards, and the advancement of, sustainable development. Especially, the effects of such technologies reinforce one another as to their efforts for transforming the processes operating and organizing urban life in a sustainable way by integrating data-centric and context-aware solutions to enhance and integrate urban systems and to facilitate collaboration and coordination among urban domains.

This seminal work provides the necessary material to inform relevant research communities of the state-of-the-art research and the latest development in the area of smart sustainable urban planning and development, as well as a valuable reference for scholars and practitioners who are seeking to contribute to, or already working toward, the development, deployment, and implementation of smart sustainable cities based on big data analytics and context-aware computing. In this respect, the upshot of this book enables researchers to focus their work on the identified challenges pertaining to and the existing gaps between smart cities and sustainable cities as established urban development strategies. Practitioners can use the outcome to identify common weaknesses and alternative solutions in sustainable urban planning and development initiatives and endeavors. While this book can best be seen as being aimed at those with a background in both computation and urban planning, it is primarily from a computation angle (it would be more appropriate for giving computer scientists a vantage on planning than giving planners a vantage on computation), yet with much valuable knowledge of relevance to urban planners.

Furthermore, its strength lies primarily in the topicality of the issues it deals with and the meaningfulness of the subjects it covers. Specifically, it covers topics of immediate relevance and importance owing to their relation to the contemporaneous phenomena of sustainable development, sustainability, urbanization, ICT, ubiquitous computing, and data science, in addition to comprising many aspects of future city life in terms of life quality, environmental quality, resource efficiency, mobility and accessibility enhancement, and so on. These are associated with the ongoing endeavors and initiatives for smartening up urban sustainability and integrating its dimensions.

Intended Readership

Smart Sustainable Cities of the Future is intended for several classes of readers, namely students, researchers, academics, data scientists, computer scientists, technologists, ICT experts, urban planners, urbanists, engineers, architectural designers, urban professionals, urban policy analysts and makers, and decision makers and leaders, whether they are new or already working or involved in the area of smart sustainable urban planning and development, as well as for all of those interested in a wide-ranging overview of contemporary urban innovations in the field. Specifically, I have written this book with two kinds of readers in mind. First, I am writing to students taking graduate and postgraduate courses or pursuing Master's and Ph.D. programs in the areas of smart cities, sustainable cities, urban design and planning, urban computing, urban informatics, urban science, urban sustainability, sustainable urban management, and so forth. Those familiar with smart cities and sustainable cities and the relationship between these two concepts or urban development approaches will certainly get more out of this book, and find much more that appeals to them in it than those without that grounding. However, those with more limited knowledge are supported with detailed explanations of the relevant conceptual, theoretical, discursive, and applied foundations with reference to the field of smart sustainable urban planning and development. This is meant to appease the uninitiated reader. Second, I anticipate that this book will be a useful resource for all of those involved or with interest in smart sustainable urban planning and development (scholars, scientists, practitioners, decision makers, futurists, etc) that are looking for an accessible and essential reference as to the interplay between the scientific and technological developments and the physical, social, and environmental dimensions of smart sustainable cities. In all, people in many academic disciplines and professional fields will find the wide-ranging coverage of the diverse strands comprising, and the multiple perspectives associated with, the flourishing field of smart sustainable cities to be of interest and value. My hope is that this book will also be suited to people of other societies than technologically and ecologically advanced nations.

Perspectives and Prospects

This book benefits indirectly from the work of many people working within, and at the intersection of, the fields of smart cities and sustainable cities. Thus, I am indebted to other writings in the sense of inspiring me into a quest for the immense opportunities created by endeavoring to integrate smart cities and sustainable cities as urban development strategies to achieve the required level of sustainability under what is labeled "smart sustainable cities of the future" in an increasingly computerized and urbanized world. This has led me to espouse an intellectually distinctive approach into writing this book so that it can offer a tremendous value with auspicious effects and be differentiated from other books on the topic on focus with regard to their emphases and scopes of scholarship, as well as to their research perspectives. This is manifested in identifying and leveraging the potential of explicitly bringing together the smart city and sustainable city endeavors in a form of a holistic urban development strategy, and in focusing on and amalgamating big data analytics and context-aware computing specifically. While this book has an ambitious goal, clearly it is not possible to deal with every aspect of smart sustainable cities in a single book, nor can it cover all of the chosen topics in equal depth. Nevertheless, it will be a great asset to relevant research and scientific communities, as well as to those who are interested in the notion of smart sustainable cities as a new techno-urban innovation or vision.

This book highlights the increasing urgency to link future discoveries in computing and emerging developments in ICT with the agenda and goals of sustainable development in the realm of smart sustainable cities, a promising urban development approach that emphasizes decoupling urban well-being and health and the quality of life of citizens from the energy use and concomitant environmental risks associated with urban operations, functions, services, designs, and policies. Indeed, current and future investments in ICT of the new wave of computing ought to be justified by environmental concerns and socioeconomic needs, thereby enabling livable and healthy human environments in conjunction with minimal demand on resources and minimal environmental impacts—rather than by sheer technical advancement and unjustified industrial competitiveness. What is mostly needed nowadays are techno-urban innovations and visions that are not driven by distant and overblown computing and ICT research agendas focused mainly on technological superiority motivated by short-term profits, narrow outlooks, and unsustained disruptive effects—but rather driven by the pursuit of the persistent delivery of robust solutions for promoting urban sustainability and stimulating research opportunities within the field.

Furthermore, this book expects to elicit fertile insights and provide new perspectives in the event of amalgamating big data analytics and context-aware computing as advanced forms of ICT in the context of urban sustainability. This is meant to bring people from different academic disciplines and professional fields or working on cross connections of computing, ICT, sustainability science, sustainable development, and urban design and planning (including scholars, academics, researchers, scientists, experts, planners, architects, engineers, administrators, and policy makers) on a common platform to design, develop, disseminate, and concretize new ideas and concepts to significantly improve the field of smart sustainable cities and to promote related programs and initiatives based on big data analytics and context-aware computing.

Additionally, I consider that this book provides a form of grounding for further discussions to debate over the point that ICT of the new wave of computing has disruptive, substantive, and synergetic implications, in particular on forms of urban functioning, management, and planning that are necessary for urban sustainability practices in the future. This book also presents a basis for encouraging in-depth research on smart sustainable cities, thorough qualitative analyses, and empirical studies focused on establishing, uncovering, and substantiating the assumptions underlying the substance behind the smart wave of sustainable urban planning and development initiatives and endeavors in an increasingly computerized and urbanized world.

Finally, I believe that I have achieved an important goal with this book—by creating a valuable and strategic resource for the research community and industry involved in the domain of smart sustainable urban development. Especially, I believe that there is an urgent need for a comprehensive book on smart sustainable cities given that the field is remarkably heterogeneous with a large number and wide variety of research questions and opportunities yet to explore. I will be pleased if this book contributes to a better understanding of smart sustainable cities of the future, and helps in stimulating their development and implementation. All in all, I hope that this book will be enlightening, thought-provoking, and, more importantly, making good reading for the target audience. And ultimately, the first edition will be well received.

Trondheim, Norway
May 2017

Simon Elias Bibri

Acknowledgements

This scholarly book as an integral part of my ongoing Ph.D. research is the fruit of rich learning experiences and valuable intellectual pursuits involving many people whom I have had the pleasure and privilege to meet during my academic studies in Sweden. I hope that our paths will cross again in the future. I am more indebted than I can possibly acknowledge to the people that have particularly contributed directly, indirectly, or unknowingly to my knowledge enrichment and intellectual development. Also, I am greatly thankful to those who have supported me throughout my academic journey, encouraged me to pursue the path of scientific research, believed in my intellectual abilities, and inspired me to become an academic author. I wish next to offer my most heartfelt thanks to those who have contributed directly and indirectly to this book, making it such an enjoyable and momentous intellectual experience.

I am deeply grateful to my main supervisor, Professor and Head of the Department of Computer and Information Science John Krogstie, for giving me the opportunity to carry out my doctoral studies in the area of smart sustainable cities of the future, playing a key role in coordinating the Ph.D. research project with the Department of Urban Design and Planning at NTNU, and allowing me to conduct my research on the interdisciplinary topic that I am truly passionate about —not forcing his interests onto me. I am also greatly thankful for his valuable comments and constructive suggestions on my drafts. His thoughtful guidance, insightful criticism, and timely support have kept me on a sound research path, while his good nature and humbleness made learning from, and sharing knowledge with, him such a delight. He has sparked several of my ideas and provided much more of an input to this book than he could probably realize. It has been a real privilege for me to share of his exceptional scientific knowledge as well as of his extraordinary human qualities.

I would also like to acknowledge and thank my co-supervisors, Professors Tor Medalen, Yngve Karl Frøyen, and Monica Divitini, for the fruitful discussions and the ensuing constructive inputs on the research path I have pursued. Their critical insights and thought-provoking questions have brought value to my research, and helped me become more self-reflective and self-critical in order to broaden my perspective of thought and thus enhance my research work. Their diverse background and research interests give their inputs a distinct intellectual flavor in respect of the approach to my research topic.

I also owe special thanks to several professors at the Department of Computer and Information Science for their willingness to share knowledge and exchange ideas through informal intellectual conversations, as well as for making me feel so welcome, especially during the first 6 months of my Ph.D. research at NTNU. I would like to take this opportunity to extend my special thanks to Research Scientist Dirk Ahlers for his constructive inputs and suggestions. I am fortunate to be part of the scientific staff at this department and to be working in this academic environment. My learning experience has hitherto been rewarding and enjoyable.

I also owe a great deal of gratitude to the administrative and technical staff at the Department of Computer and Information Science for their constant support and immense help delivered throughout my Ph.D. studies. In particular, I am very thankful to Ellen Marie-Therese Solberg, who has been of much help with every possible practical and administrative matter. She is uniquely approachable and has been an ever present beacon of support, keeping her office door open and available for all the times when people need it. The administrative and technical staff has contributed tangibly to providing a working environment conducive to knowledge production and intellectual inspiration. The surrounding ambience has been so favorable that I personally felt, only after one year of conducting research, that it was the most auspicious time to start writing a scholarly book and contribute with it to the research community. This was way earlier than I have ever anticipated. In a nutshell, the vibe of the academic atmosphere at NTNU, coupled with flexible working hours, has been instrumental in boosting my intellectual productivity.

I also owe a debt of gratitude and appreciation to Prof. Diamanto Politis and Prof. Jonas Gabrielsson at Halmstad University, Sweden, for their unfailing encouragement, unwavering support, and readiness to give of their time and share their valuable knowledge and experience, as well as for being close academic friends of mine. They are the best professors I have ever had the privilege to have known during my long academic journey in Sweden. They are incredibly thoughtful and wonderfully kind people. I hold them in highest regard in respect of their humbleness, moral fiber, and integrity.

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Contents

About the Author

Simon Elias Bibri is a Ph.D. scholar in the area of smart sustainable cities of the future and Assistant Professor at the Norwegian University of Science and Technology (NTNU), Department of Computer and Information Science and Department of Urban Design and Planning, Trondheim, Norway. His true passion for academic and lifelong learning, coupled with his natural thirst for interdisciplinary and transdisciplinary knowledge, has led him to wittingly and voluntarily pursue an unusual academic journey by embarking on studying a diverse range of subject areas—at the intersection of computer science, information science, environmental science, and the social and human sciences. His intellectual pursuits and endeavors have hitherto resulted in an educational background encompassing knowledge from, and meta-knowledge about, different academic and scientific disciplines. He holds the following academic degrees:

- Bachelor of Science in computer engineering with a major in ICT management and strategy
- Master of Science in computer science with a major in ICT for sustainability
- Master of Science in computer science with a major in informatics
- Master of Science in computer and systems sciences with a major in decision support and risk analysis
- Master of Science in entrepreneurship and innovation with a major in new venture creation
- Master of Science in strategic leadership toward sustainability
- Master of Science in sustainable urban development and planning
- Master of Science in environmental science with a major in eco-technology and sustainable development
- Master of Social Science with a major in business administration (MBA)
- Master of Arts in communication and media for social change
- Postgraduate degree (one year of Master courses) in management and economics
- Ph.D. in ICT with a major in smart sustainable cities of the future (underway).

Bibri has earned all his Master's degrees from different Swedish universities, namely Lund University, West University, Blekinge Institute of Technology, Malmö University, Stockholm University, and Mid Sweden University.

Before embarking on his long, still ongoing, academic journey, Bibri served as a sustainability and ICT strategist, business engineer, consultant, and researcher. Over the past few years and in parallel with his academic studies, he has been involved in a number of research and consulting projects pertaining to green ICT strategy, big data analytics, strategic sustainability innovations, sustainable business model innovation, sustainable urban planning, and green and social innovation.

Bibri's current areas of research work include smart sustainable cities; Ambient Intelligence (AmI), Ubiquitous Computing (UbiComp), the Internet of Things (IoT), and Sentient Computing (SenComp) as well as how these computing paradigms relate to urban sustainability, sustainability science, urbanization, and urban design and planning; and big data analytics and context-aware computing and the associated core enabling technologies, namely sensor technologies, data processing platforms, cloud and fog computing infrastructures, middleware architectures, and wireless communication networks.

Bibri has a genuine interest in interdisciplinary and transdisciplinary research. In light of his multidisciplinary academic background, his research interests include the following areas:

- ICT of pervasive computing
- Big data analytics and context-aware computing for sustainability
- Sustainable urban planning and development
- Sustainable city models (eco-city, compact city, green urbanism, new urbanism, etc.)
- Smart city approaches (ambient city, ubiquitous city, sentient city, real-time city, etc.)
- Sustainability transitions and socio-technical shifts
- Green innovation and knowledge-intensive entrepreneurship
- Philosophy and sociology of scientific knowledge
- Social construction and shaping of science-based technology
- Technological and national innovation systems
- Sustainable business model innovation
- Technology, innovation, and environment policy.

Bibri is the author of two recently published books in the field of pervasive computing, in addition to a forthcoming book in the area of smart sustainable urban planning and development. Also, he has occasionally been working on his fourth book in parallel with his doctoral studies. The titles of these books are as follows:

1. The Human Face of Ambient Intelligence: Cognitive, Emotional, Affective, Behavioral and Conversational Aspects (523 pages), Springer, 07/2015.
2. The Shaping of Ambient Intelligence and the Internet of Things: Historico-epistemic, Sociocultural, Politico-institutional and Eco-environmental Dimensions (301 pages), Springer, 11/2015.

3. Smart Sustainable Cities of the Future: The Untapped Potential of Big Data Analytics and Context-Aware Computing for Advancing Sustainability (650 pages), Springer, 2018.
4. Unprecedented Shifts in the Philosophy and Sociology of Sustainability Science in the Exabyte Age: The Unique Potential and Power of the Big Data Deluge (350 pages).

Chapter 1
Introduction: The Rise of Sustainability, ICT, and Urbanization and the Materialization of Smart Sustainable Cities

Abstract Opening the book as a scene-setting chapter, this chapter provides a detailed introduction: background, literature review, aim and objectives, and motivations, as well as the structure of the book and its contents. This thorough introductory chapter, as a by-product of its intent, consists in a comprehensive overview of the blossoming interdisciplinary field of smart sustainable cities in terms of its underlying theoretical and discursive foundations and assumptions, state-of-the-art research, up-to-date developments, research opportunities and horizons, emerging scientific trends, major global shifts, and future planning and development practices. The relevant topics, questions, and knowledge gaps pointing to a need for meaningful and deliberate investigation are introduced in this chapter, and will be developed further, analyzed, evaluated, and discussed in the subsequent chapters as part of the systematic exploration of the subject of smart sustainable cities of the future.

Keywords Smart cities · Sustainable cities · Smart sustainable cities
Urbanization · Sustainability · Sustainable development · Big data analytics
Context-aware computing · ICT · Computing

1.1 Extended Background

1.1.1 Global Shifts at Play Across the World: The Dynamic Interplay Between Sustainability, ICT, and Urbanization

The rise of ICT, the diffusion of sustainability, and the spread of urbanization are the three most important global trends at play across the world today. They all remain unprecedented in their magnitude and influence in history, and will most likely change the way we live drastically and irreversibly. As these trends will undoubtedly continue to evolve simultaneously, we can reasonably expect that the world will become largely computerized and urbanized within just a few decades,

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and that ICT as an enabling and constitutive technology will have a key role in winning the battle of sustainability and in addressing the conundrums posed and issues engendered by urbanization. It is therefore an obvious and yet unsurpassed opportunity to use advanced ICT to understand and rise to the challenges of sustainability and urbanization in new ways, and to resolve the many intractable and wicked problems involved in urban management, planning, and development. In fact, there is an increasing recognition that ICT constitutes a promising response to such challenges and problems due to its tremendous untapped potential to catalyze and advance sustainable development (Bibri and Krogstie 2016a). Strengthening the role of digital technologies has actually been, and continues to be, supported by constant endeavors to further unlock the transformational effects of ICT by exploiting and capitalizing on its disruptive and innovative power in relation to urban systems and domains and how these can be integrated and coordinated for increasing sustainability performance in contemporary cities. These are indeed seen as one of the most challenging and yet enabling arenas for achieving the goals of sustainability. This is predicated on the assumption that as the rapid urbanization will jeopardize the sustainability of cities (Neirotti et al. 2014), it will also drive and spur sustainability innovation. Hence, governments are currently seeking to transform their cities by embracing ICT and sustainability and thus to face urbanization and related challenges. To ensure the effectiveness of such transformation, urgent urban needs, emerging trends, urban readiness for the upcoming change, available resources and technological capabilities, and smart initiatives and solutions directed for sustainable transformation should be considered. These entail devising comprehensive frameworks and roadmaps for organizing and launching concrete projects and programs, supported by long-term visions and related strategies and immediate policy measures for guiding and sustaining the needed transformative processes.

Currently, more than half, and by 2050 more than two-thirds (66%), of the world's population is expected to be urbanized or live in cities (United Nations 2015). Every second, the global urban population increases by 2 people, and soon will exceed 3.9 billion people. This unprecedentedly rapid urbanization in history taking place since the beginning of the last century signifies that the world is fast moving to cities and for the long term. This implies significant challenges for city governments associated with environmental, economic, and social sustainability due to the issues engendered by urban growth in terms of intensive energy consumption, endemic congestion, saturated transport networks, air and water pollution, toxic waste disposal, resource depletion, environmental degradation, inadequate decision-making and planning systems, inefficient management of urban infrastructures and facilities, poor housing and working conditions, social inequality and vulnerability, public health decrease, and so on (Bibri and Krogstie 2017a), although urbanization epitomizes an emblem of social evolution. In short, the multidimensional effects of urban unsustainability are most likely to exacerbate with urbanization. In other words, urbanization will aggravate the unsustainability of cities. Indeed, urbanization as a dynamic clustering of people, buildings, and resources puts an enormous strain on the limited urban resources and affects the resilience to the growing demands on them, and urban management and governance face ever-mounting challenges. To disentangle these intractable problems requires evidently unprecedented shifts in urban thinking and planning—i.e., newfangled ways founded on more innovative and effective solutions and approaches with respect to how cities can be conceived of, managed, and developed (Bibri and Krogstie 2017a). This is crucial to rise to the substantial challenges arising from the rapid urbanization (and continuous unsustainability) of the world. In this regard, ICT innovations can provide integrated information intelligence for enhancing urban operational functioning, management, planning, design, socioeconomic forecasting, and policy development on the basis of participatory, poly-centric, and digital models and processes of governance. Besides, the planning of cities as complex systems and dynamically changing environments in terms of how they function and can be managed and developed requires innovative solutions as well as advanced approaches to understand them.

Against the backdrop of the unprecedented rate of urbanization, alternative ways of thinking about, conceiving of, and planning cities based on advanced ICT are materializing as to how cities can transition toward the needed sustainable development. This can be attained through adopting a set of integrated frameworks, procedures, processes, strategies, and policies to foster advancement and innovation in urban systems, namely built environment, infrastructure, administration, governance, and ecosystem and human service provisioning, while continuously optimizing efficiency gains. An increasing urgency to find and adopt smart solutions is driven by the rapid urban growth in terms of seeking out ways to address and overcome the associated challenges and ensuing effects pertaining to sustainability (Bibri and Krogstie 2017a; Nam and Pardo 2011). Townsend (2013) portrays ICT development and urban growth as a form of symbiosis. This entails an interaction that is of advantage to, or a mutually beneficial relationship between, ICT and urban growth (Bibri and Krogstie 2017a). One way of looking at this is that urban growth can open entirely new windows of opportunity for cities to act as vibrant hubs of technological innovation in the context of environmental, economic, and social sustainability, which can be driven by and focused on solving the challenges stemming from urbanization in the path to meet the goals of sustainable development. Indeed, a large number and variety of new technologies and applications are being developed and applied in response to the urgent need for dealing with the complexity of the knowledge necessary for addressing and overcoming the challenges of urbanization and sustainability in terms of novel and powerful decision-making systems and urban intelligence functions for operating, managing, and planning urban systems as well as for coordinating and integrating urban domains. Modern cities as characterized by the rapid urbanization must take greater advantages of emerging and future technologies to be able to move with the times as to handling their operations, functions, designs, services, strategies, and policies. We are at a critical point in this evolution as new technological and societal forces are merging to create new and needed approaches into urban management, planning, development, and governance. In all, there is an urgent need for developing and applying innovative solutions and sophisticated methods to overcome the challenges of urbanization (United Nations 2016) and sustainability (Batty et al. 2012; Bibri and Krogstie 2017a, b). Across the globe, city governments are attempting to overcome such challenges through emerging technologies given their pivotal role in enabling new models, processes, methods, techniques, and practices informed by the evolving trend and shift of urbanization and aimed at transforming cities to function constructively, safely, efficiently, and sustainably. While the approaches to such transformation have been evolving for some time, what is new to this process is that urban initiatives and endeavors are well moving from merely focusing on the development and deployment of technologies to connecting them more and more to solutions focused on the expected effects of urbanization in terms of enhancing service delivery, the quality of life of citizens, and urban operational functioning (resources, infrastructures, facilities, networks, etc.) as well as urban planning and policy analysis. This enhancement is inextricably linked to the goals of sustainability.

Essentially, sustainability envisions a future in which environmental, economic, and social considerations are equitable in the pursuit of an improved lifestyle of city residents and increased gains of city collective actors. However, most of the major cities in the world are becoming epicenters of unsustainable development and evolving with breakneck velocities, a dire situation that is caused by the immense utilization of natural resources, inefficient operation, and management of urban infrastructures and facilities, waste and pollution generation, and ecological deprivation and irresponsibility. In light of these occurrences, contemporary debates in urban and academic circles are increasingly focusing on the role of sustainability (in conjunction with ICT) in urban planning and development in terms of responding to the enormous challenges arising from, in addition to the rapidly evolving urbanization, the unsustainability of the forms of cities. Sustainability as a thinking paradigm and holistic approach remains thus far the most effective way to enable cities to better cope with urban changing dynamics and restructuring demands. This is to mitigate the adverse effects that cities will encounter when stretching beyond the capacities of urban systems as a result of urban growth and concurrently address the problems of the form of contemporary cities. Urban systems—i.e., the processes that operate and organize urban life in the form of built form, infrastructure, ecosystem services, human services, and administration—are under increasing pressure due to the challenges of sustainability and urbanization. In particular, the existing built environment is associated with numerous environmental, social, and economic impacts, including unsustainable energy use and concomitant greenhouse gas (GHG) emissions, increased air and water pollution, environmental degradation, land use haphazard, outdated (nonautomated, non-digital) infrastructures, inappropriate urban design and related social deprivation and community disruption, ineffective mobility and accessibility, increased transport needs and traffic congestion, and public safety and health decrease, but to name a few. In a nutshell, the form of contemporary cities has been viewed as a source of environmental, social, and economic problems, and thus has negative implications for citizens, natural resources, habitat, and the environment. These effects are set to worsen due to the issues engendered by urbanization and unsustainable urban design, land use, and transportation. Urban growth raises a variety of problems that tend to jeopardize the environmental, economic, and social sustainability of cities (e.g., Neirotti et al. 2014). Nevertheless, to overcome the intractable problems related to the unsustainability of the form of cities requires evidently unprecedented shifts in urban thinking and planning emphasizing a holistic system perspective with respect to the conception and development of the built form of cities and its associated infrastructural, operational, organizational, and functional processes. Toward this end, it is urgent and necessary to develop and apply advanced technologies and what they entail in terms of applications, methods, models, and services as innovative and smart solutions. Thereby, ICT has become part of mainstream debate on urban sustainability due to the ubiquity presence of computing and the massive use of technology in urban systems and domains. Indeed, data sensing and information processing are being fast embedded into the very fabric of contemporary cities while wireless networks are proliferating on a hard-to-imagine scale. Against the backdrop of the unsustainability of the form of contemporary cities, alternative ways of conceiving of, designing, and developing cities through the lens of advanced ICT are emerging as to how they can increase their contribution to the goals of sustainable development. Indeed, the way cities can be designed and developed with support of advanced ICT has been of utmost importance to strategic sustainable development to achieve the long-term goals of sustainability (Bibri and Krogstie 2017a). To put it differently, ICT in its various forms (infrastructures, architectures, applications, systems, computational and data analytics capabilities, and services) is increasingly seen to provide unsurpassed ways to address a range of complex environmental challenges and rising socioeconomic concerns facing contemporary cities. ICT is already enabling cities in many parts of the world to remain sustainable and thus livable and attractive in the face of environmental pressures, growing social mobility, and economic restructuring. Besides, the planning of cities toward sustainability requires innovative solutions and sophisticated methods. This entails the application of computer science, data science, and complexity sciences upon which emerging urban ICT is founded. Indeed, many new technologies and applications are being developed and applied in response to the urgent need for addressing the challenge of the unsustainability of the built form in terms of devising powerful urban intelligence functions and simulation models for designing and developing the built environment as part of smart sustainable urban development (Bibri and Krogstie 2017b). ICT innovations, coupled with increased sustainability awareness and adoption, are resulting in a unique opportunity to rethink the way we design and develop cities and to develop new ways of understanding and addressing urban challenges.

As the engines of economic growth, cities are major consumers of energy resources and significant contributors to GHG emissions. They consume 67% of the global energy demand and generate up to 70% of the harmful GHG emissions (e.g., Creutzig et al. 2015). Thus, they represent key generators of environmental pollutants and main hotspots of vulnerability to climatic hazards and natural disasters resulting from climate change, as well as present complex challenges for social inequality and disparity. This is due to the density of urban population and the intensity of related economic and social activities, coupled with the inefficiency of the built environment. Therefore, they have increasingly gained a central role in applying the discourse of sustainable development and are seen as the most important arena for sustainability transitions because they constitute key sites of economic, environmental, and social dynamism and innovation making significant contributions to sustainable transformations and hence social evolution and cultural advancement. For instance, urban strategies (e.g., urban design concepts, principles, and policies) through which sustainable cities can be achieved allow for resource efficiency of buildings, traffic congestions reduction, pollution alleviation, low-carbon mobility, accessibly enhancement, sustainable and efficient transportation, green urban planning, quality of life enhancement, and land use minimization, but to name a few. Several contrasting roles and functions of cities underscore immense opportunities to utilize their momentum and talent toward more sustainable development pathway. Specifically, cities can, through sustainability-oriented innovations, evolve in ways that address environmental concerns and meet socioeconomic needs. They are the incubators, generators, and transmitters of creative ideas and innovative solutions for solving many challenges and problems (Bibri and Krogstie 2017a).

The dynamic interplay between sustainability, ICT, and urbanization is the backcloth against which many different initiatives in innovation and transition have evolved, and continue to be witnessed, the materialization and proliferation of groundbreaking ways of thinking about and conceiving of how cities could adopt sustainability innovations and enable transitions to the needed sustainable development with support of advanced ICT in order to contain the intended effects and address the imminent challenges of urbanization. Accordingly, the urban world has evolved substantively since the concept of sustainable development was applied to urban planning and design in the early 1990s, not least in ecologically and technologically advanced nations. As a paradigm change in societal thinking of a kind that is unprecedented, sustainability has been determining in instigating, engendering, and shaping major shifts in the core practices, primary operations, and central institutions of such nations in response to the challenge of sustainability. Several other technologically advanced nations are exhibiting drastic shifts in response to the global calls for tackling the pressing issues of urbanization by finding the most innovative solutions to the related problems. This is increasingly being fueled by the recent advances in ICT and its embeddedness into the very fabric of contemporary cities. In these two classes of nations, urban systems are becoming complexly and intricately interconnected and urban domains are increasingly getting heavily networked and coordinated, thereby giving rise to new classes or faces of cities that must rely on the use of more sophisticated technologies and more innovative solutions to realize their potential as to responding to the environmental and socioeconomic challenge of sustainability in an increasingly urbanized world. ICT has made it possible to approach a whole range of issues around sustainability and urbanization from new perspectives.

1.1.2 A State-of-the-Art Overview of the Field of Smart Sustainable Cities

1.1.2.1 Smart (and) Sustainable Urbanism: Key Contributions, Issues, and Challenges

When discussing sustainability, ICT, and urbanization and thus sustainable and smart practices and solutions for cities characterized by the rapid urbanization, reference is often made to three concepts: sustainable cities, smart cities, and smart sustainable cities. During the late 1980s the discourse on sustainable cities focused on the environmental, social, and economic sustainability of cities, and during the 1990s, the focus turned to the discourse on smart cities emphasizing ICT as a lens to see the future urban development. ICT has since gained recognition that it can contribute to transforming cities into spaces that can adapt to environmental, societal, and economic shocks. Compared to smart cities and sustainable cities, which have been around for quite sometime, smart sustainable cities have come to light over the past few years. Not until very recently, the smart sustainable urban development approach has attracted significant attention among contemporary urban scholars, planners, and policymakers. Its insertion, functioning, and evolution as a discourse, social practice, and techno-urban innovation are increasingly shaped and influenced by technological, societal, and economic factors: ICT industry consortia, research institutes, governments, policy networks, triple helix of university–industry–government relations, and recent quadruple university–industry–government–citizen relations, not least in ecologically and technological advanced societies (Bibri and Krogstie 2016a, 2017a). While there is a growing interest in this flourishing, interdisciplinary field of research, the academic discourse of smart sustainable urban development within the relevant literature is still scant—yet rapidly burgeoning. Indeed, a few studies exploring the subject of smart sustainable cities have been published in mainstream journals. The case is evidently different from smart cities and sustainable cities as urban development strategies, which have witnessed a proliferation of academic publications and thus varied emphases of research and a large body of practices. However, the speed at which the field of smart sustainable cities is gaining momentum and attracting attention gives a clear indication of its developmental path, blossoming nature, and future direction. In fact, this field of research comes as a natural pursuit within urban planning and development in light of the unsolved and unsettled issues and intellectual challenges pertaining to existing models of sustainable urban form in terms of their contribution to the goals of sustainable development, as well as the deficiencies and misunderstandings associated with existing smart city approaches in terms of their explicit incorporation of the goals of sustainable development.

Sustainable Cities (Urban Forms)

Sustainable development has significantly shaped and influenced the development of city models in terms of different dimensions of sustainability. Unquestionably, it has inspired and motivated a generation of urban scholars and practitioners into a quest for the immense opportunities created by the development of sustainable urban forms—i.e., the contribution that such forms can make as to lowering energy use and lessening pollution and waste levels, while improving human life quality and well-being (Bibri and Krogstie 2017a, b). Scholars from different disciplines and practitioners from different professional fields have, over the past two decades or so, sought a variety of sustainable city models that can contribute to sustainability and its continuous improvement. Compact city, eco-city, green urbanism, and new urbanism are the most widely applied sustainable city models (e.g., Bibri and Krogstie 2017b). The underlying challenge continues to motivate and induce scholars and practitioners as well as policymakers and decision makers to work collaboratively to put forward new models for redesigning and rearranging urban areas across many spatial scales to achieve the required level of sustainability, especially in relation to integrating its physical, environmental, economic, social, and cultural dimensions. The ultimate goal revolves around developing more convincing and robust models. This has been one of the most significant intellectual challenges and research endeavors for more than two decades. This implies that it has been difficult to, in addition to translating sustainability into the built form of cities, evaluate the extent to which the so-called sustainable urban forms contribute to the goals of sustainable development and to strategically improve this contribution. Indeed, existing models of sustainable urban form still pose several conundrums and raise numerous issues—when it comes to their development and implementation as to their contribution to the fundamental goals of sustainable development (Bibri and Krogstie 2017a). This pertains to limitations, uncertainties, paradoxes, and fallacies. The main premise is that urban systems have been in themselves complex in terms of their operation, management, assessment, and planning, so too are urban domains in terms of their coordination, integration, and coupling, all in the context of sustainability. To put it differently, whether in discourse, theory, or practice, the issue of sustainable urban form has been problematic and difficult to deal with, and research results tend to be uncertain, weak, limited, divergent, and not conclusive, particularly when it comes to the actual effects of the claimed benefits of sustainability (Bibri and Krogstie 2017a, b). Regardless, Neuman (2005) contends that conceiving cities in terms of forms remains inadequate to achieve the goals of sustainable development; or rather, accounting only for urban form strategies to make cities more sustainable is counterproductive. Instead, conceiving cities in terms of "processual outcomes of urbanization" holds great potential for attaining the goals of sustainable development, as this involves asking the right question of "whether the processes of building cities and the processes of living, consuming, and producing in cities are sustainable," which raises the level of, and may even change, the game (Neuman 2005). This process-driven perspective paves the way for a dynamic conception of urban planning that reverses the focus on urban forms governed by static planning tools; this holds more promise in attaining the elusive goals of sustainable development (Neuman 2005). This argument provides valid reasons (supported with the above discussion) to believe that the conclusion it supports is true. This validity is in accordance with the fact that it is timely and necessary to develop and apply innovative solutions to deal with the challenges of sustainability and urbanization and how they affect each other in the context of sustainable urban forms. This would necessitate a blend of sciences for creating advanced engineering solutions, which ICT is extremely well placed to initiate given that it is grounded in the application of data science, computer science, and complexity sciences to urban systems and domains and related intractable problems (see, e.g., Batty et al. 2012; Bibri and Krogstie 2017a, b). One way forward to smarten up sustainable urban forms and thus tackle the current complex issues in an increasingly urbanized word is to adopt the cutting-edge solutions being offered by ICT of the new wave of computing and the associated big data and context-aware technologies and their novel applications (Bibri and Krogstie 2017a, b). These solutions involve constellations of instruments encompassing sensing technologies, data processing platforms, cloud computing and middleware infrastructure, and wireless communication networks as well as their use within diverse urban systems and domains of sustainable urban forms in terms of collecting, storing, coordinating, managing, processing, and analyzing continuous data on urban activities, processes, and citizens as to the flow of decisions about the physical, infrastructural, spatiotemporal, operational, functional, and socioeconomic aspects of such forms. The whole idea is that more innovative solutions are needed to overcome the kind of wicked problems associated with sustainable urban forms. In this regard, the main and relevant question is how such forms should be monitored, understood, analyzed, evaluated, and planned to strategically advance their contribution to sustainability. In fact, with their domains becoming subtly interconnected and their processes highly dynamic, sustainable urban forms are relying more and more on sophisticated technologies, and in the near future, the core enabling technologies of ICT of the new wave of computing will be the dominant mode of monitoring, understanding, analyzing, evaluating, and planning many sustainable cities (Bibri and Krogstie 2017b). In addition, cities are increasingly seen as adaptive and data-centric systems, characterized by dynamic changes, complex interactions, and multidimensional effects, in contrast to what was the case for 50 years ago when cities were still very much seen as unchanging structures and relatively closed systems. Accordingly, context information and big data from various urban domains as a strategic asset constitute the fundamental ingredients for the next wave of urban analytics and planning. In all, it has become highly relevant and important in an increasingly computerized and urbanized world to amalgamate the design and planning concepts and principles of sustainable urban forms with smart solutions and sophisticated methods for the purpose of strategically assessing and optimizing the contribution of such forms to sustainability under what is labeled “smart sustainable cities of the future.” Worth noting is that for many contemporary urban scholars, theorists, and planners, the design concepts and typologies of such forms are necessary to be adopted and implemented to achieve the goals of sustainable development (e.g., Jabareen 2006; Dumreicher et al. 2000; Leccese and McCormick 2000; Williams et al. 2000)—irrespective of how intelligently the underlying urban systems and domains can function and be managed, designed, and planned (Bibri and Krogstie 2017a, b).

Smart Cities

While the development of sustainable urban forms based mostly on city design and planning has been, for about two decades, the preferred response to the challenge of sustainability (e.g., Bibri and Krogstie 2017a; Jabareen 2006; Kärrholm 2011), the development of smart city has come to the fore in recent years as a promising response to the same challenge (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Neirotti et al. 2014)—by developing smart solutions for sustainability (climate, energy, transport, etc.), optimizing efficiency in urban operational functioning, devising and applying a smart approach into urban design and planning, and enhancing the quality of life and well-being of citizens (e.g., Bibri and Krogstie 2017a). This is increasingly contributing to the further integration of urban systems and the effective assessment of their performance in terms of sustainability; optimizing urban operations and processes; enhancing and mainstreaming ecosystem and public services; and pinpointing which urban domains, facilities, and networks need to be coupled, coordinated, and amalgamated. The smart solutions have proven to improve many practices in large cities in terms of sustainability, efficiency, and the quality of life. It is in smart cities that the key to a better world—which is held by ICT—will be most evidently demonstrated (Batty et al. 2012). The prosperity of many cities and their ability to address complex challenges through advanced ICT is one of the key reasons why much attention has been given to smart cities as an urban development strategy. Cities can evolve in ways that address environmental concerns and respond to socioeconomic needs using smart solutions (e.g., Bibri and Krogstie 2017a). Nowadays, smart cities are considered as an effective way to control climatic change by monitoring environmental indicators and targets, as well as adopt novel technologies to improve the well-being of citizens and to foster economic development. They are focused on managing resources and infrastructures safely, efficiently, and sustainably to improve societal and economic outcomes. However, like sustainable city models, existing smart city approaches present significant challenges and raise many issues—when it comes to their actual development and implementation with regard to the explicit incorporation of the fundamental goals of sustainable development. This pertains to deficiencies, inadequacies, and misunderstandings as well as a lack of accounting for environmental concerns and risks. But what is of most relevance to highlight is that there is a weak, or a lack of, connection between smart cities and sustainable cities, despite the great potential and proven role of ICT in supporting cities in their transition toward sustainability, especially in relation to the operation, management, and planning of urban systems and the coordination and integration of urban domains (e.g., Bibri and Krogstie 2017a, b). It is important to understand how the concepts of smart cities and sustainable cities relate to each other (Bifulco et al. 2016).

Smart Sustainable Cities

In light of the above, recent research endeavors have started to focus on incorporating sustainability in smart city approaches and on smartening up the contribution of sustainable city models to the goals of sustainable development (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Kramers et al. 2014; Neirotti et al. 2014; Shahrokni et al. 2015). Yet, the optimal way of doing this as crystallized in urban and academic circles not long ago is through amalgamating the two urban development strategies in an attempt to achieve the required level of sustainability with respect to operations, functions, services, designs, and policies under what is labeled "smart sustainable cities" of the future. This entails unlocking the potential of ICT of the new wave of computing to provide the technological infrastructures, solutions, and approaches needed for advancing the contribution of sustainable urban forms to the goals of sustainable development based on an effective integration of the typologies and design concepts of such forms with big data analytics and context-aware computing in terms of the underlying core enabling technologies and their novel applications. At present, there in fact exists a competition on how to interpret and operationalize the concept of smart sustainable cities (e.g., Al-Nasrawi et al. 2015). Several ecologically and technologically advanced nations aim at being associated with it as a sign of (smart sustainable) development. While some countries claim to have evolved toward smart sustainable cities, and others to have developed the technical infrastructure needed for smart sustainable cities and focused on sustainable development policies, there is no hard evidence to confirm these claims as there is still no assessment models and frameworks to measure the performance of such cities (Al-Nasrawi et al. 2015; Bibri and Krogstie 2017a). Nevertheless, smart sustainable cities as a notion have a positive connotation. In more detail, the concept of smart sustainable cities aims at substantiating the growing significance and role of ICT in enabling both smart cities and sustainable cities to realize their potential by getting smarter in improving their contribution to sustainability and rising to the challenge of urbanization. Therefore, the concept of smart sustainable cities has come to the fore, and is rapidly gaining momentum as an academic pursuit and holistic approach to urban development, not least in ecologically and technologically advanced societies (Bibri and Krogstie 2016a, 2017a). That is to say, it is becoming increasingly an important concept not only in urban research and planning, but also in city policy and politics, thereby generating worldwide attention as a powerful framework for strategic smart sustainable urban development (see, e.g., Al-Nasrawi et al. 2015; Bibri and Krogstie 2016a, 2017a, b; ITU 2014; Höjer and Wangel 2015; Kramers et al. 2016; Rivera et al. 2015). In discursive terms, the discourse of smart sustainable cities is becoming powerful and established, as contemporary urban scholars and planners relate to it in a structured way in many contexts of their practices—institutionalized and socially anchored actions. Especially, in more recent years, smart cities have been criticized for their lack of incorporating environmental sustainability (e.g., Ahvenniemi et al. 2017; Bibri and Krogstie 2017a; Höjer and Wangel 2015; Kramers et al. 2014) and sustainable cities for facing difficulties as to translating sustainability into the built form and for evaluating the extent to which they contribute to the goals of sustainable development. In light of this, the concept and development of smart sustainable cities aim at substantiating the growing significance and role of ICT in enabling smart cities and sustainable cities to realize their potential by getting smarter as to improving their contribution to sustainability and rising to the challenge of urbanization, thereby evolving into more integrated urban development strategies. The idea of smart sustainable cities is seen as a promising approach into decoupling urban well-being and health and the quality of life of citizens from the energy consumption and concomitant environmental risks associated with urban operations, functions, services, and designs. Besides, we live in a world where ICT has become deeply embedded into the very fabric of contemporary cities, i.e., urban systems as a set of operating and organizing processes of urban life are pervaded with computer and information intelligence and high levels of automation. It follows that it is high time for sustainable cities to smarten up and smart cities to get smarter in an increasingly urbanized world. In particular, for the existing sustainable cities to advance their contribution to sustainability, they need to leverage their informational landscape by embracing what ICT has to offer as innovative solutions and sophisticated methods to make urban living more sustainable and attractive over the long run in an increasingly computerized and urbanized world. This is predicated on the assumption that ICT offers tremendous potential for monitoring, understanding, probing, assessing, and planning cities, which can be leveraged in the advancement of sustainability. In more detail, it has become theoretically and practically of high pertinence and importance to amalgamate the design concepts and typologies of sustainable urban forms with smart methods for the purpose of evaluating their practicality so to either substantiate or optimize it. Adding to this is to a augment those design concepts and typologies with smart applications for the purpose of increasing this contribution under what is labeled “smart sustainable cities of the future.” This is of high relevance to consider in an increasingly computerized and urbanized world. These insights are meant to stimulate research opportunities for rethinking the theoretical foundations of sustainable urban forms to enhance the existing practices given the relevant potential of emerging and future ICT.

One of the significant intellectual challenges pertaining to the practical use of the concept of smart sustainable cities is to develop and implement robust assessment methods and practices (metrics and their continuous evaluation) to ensure that such cities are in fact (intelligently) sustainable (Bibri and Krogstie 2017a; Höjer and Wangel 2015). This involves taking a holistic approach into evaluating the effects of ICT solutions on different dimensions of sustainability. It is worth mentioning again that one of the key challenges in the realm of sustainable cities has long been to develop and apply methods for identifying which kinds of solutions (combining design and planning concepts, infrastructural systems, environmental and urban management systems, and environmental technologies, etc.) are needed, and also for evaluating the effects of these solutions in terms of their contribution to the goals of sustainable development based on a systemic perspective.

1.1.2.2 Smart (and) Sustainable Cities: Research Issues and Challenges

As a new techno-urban phenomenon, smart sustainable cities are rapidly gaining momentum as a promising response to the challenges of sustainability in an increasingly computerized and urbanized urban world. The concept only became widespread during the mid-2010s as a result of several intertwined global trends and shifts (Bibri and Krogstie 2017a). It came to light due to the spread of urbanization and the advance of ICT in conjunction with the quest for achieving the long-term goals of sustainability. The interlinked development of sustainability awareness, urban growth, and ICT development have recently converged under what is labeled "smart sustainable cities" (Höjer and Wangel 2015). More specifically, the concept has emerged from several different developments, most notably sustainable cities, smart cities, urban computing and ICT, sustainable development, sustainability science, and urbanization. It has attracted the attention of many researchers and practitioners in the field as a desired goal for future smart sustainable urban development. Driven by the idea of ensuring that cities can offer improved living conditions to their citizens on many scales, which span over the technological, economic, and social regulatory aspects of living, smart sustainable cities emphasizes that ICT plays a crucial role in providing, and offers high potential for, solutions to many of the issues and challenges faced by cities while ensuring being viable to the environment.

The field of smart sustainable cities is still in its early stages of development, and therefore there is a wide range of research problems and opportunities to explore and embrace respectively. There are many critical questions to address concerning conceptual, theoretical, analytical, empirical, discursive, ethical, and practical aspects. The endeavors to investigate such problems constitute research opportunities in the field of smart sustainable cities, which are open to diverse scholars and practitioners to consider. The current research issues in the field of smart sustainable cities pertain to deficiencies, inadequacies, and misunderstandings pertaining to smart cities, and to limitations, uncertainties, paradoxes, and fallacies concerning sustainable cities (urban forms) with regard to the contribution to the goals of sustainable development (Bibri and Krogstie 2017a). Adding to these issues is the weak or lack of connection between smart cities and sustainable cities, despite the proven role of ICT in supporting cities in their transition toward the needed sustainable development.

Key Shortcomings of Smart Cities and Sustainable Cities

Here we present a tabulated version of the shortcomings of smart cities and sustainable cities (see Tables 1.1 and 1.2), which are distilled based an extensive interdisciplinary literature review carried out by Bibri and Krogstie (2017a) on the field of smart (and) sustainable cities in terms of its state-of-the art research and development, among other things.

Table 1.1 Shortcomings of smart cities

Shortcomings of smart cities
• A lack of a shared definition and a difficulty in identifying a common trend • Multiplicity and diversity of definitions and exacerbating confusion in the field • Misunderstanding and vagueness of existing definitions • Deficiencies in the explicit incorporation of the goals of sustainable development • The concept saying little about whether there needs to be any substance behind the claim of smartness or how that links to sustainability • Discrepancies between technological solutions and urgent problems • Smart projects dependent on target objectives, available resources, financial capabilities, and urban politics and policy—rather than on a clearly focused approach or strategy • Mismatch between smart targets and sustainability goals • Gaps between theory and practice and visions and implementations (e.g., environmental sustainability) • Multiple ICT orientations, technology development paths, and meanings of smartness • Inconsistent sets of the technological components comprising the infrastructure of smart cities • Divergences in what constitutes smart cities as to the relevance of the applications being offered • Locally- and socially-oriented understanding, development, and implementation of smart cities • Fragmented research field due to its ill-defined character and scattered research programs, thereby fostering discontinuity • Smart perspectives being too diverse to resolve • Inability of the field to proceed in anything like a cumulative fashion and to contribute systematically and constructively to the design and development of smart technologies • Versatility of available assessment models hampering the creation of a rather holistic assessment framework for steering integrated challenges • Smart technologies being less focused on improving the goals of sustainable development or providing solutions for urgent and pressing issues in relevance to sustainability • Smart technologies providing pre-configured or pre-formatted solutions for yet-to-find urban problems • Assessment frameworks lacking environmental indicators and overemphasizing economic aspects • Assessment performance frameworks focusing mainly on output indicators for measuring the efficiency of the deployed smart solutions • ICT research, innovation, and application directed mainly toward economic growth • ICT progress happening ad-hoc when new technologies and their applications become available, rather than being grounded in a theoretically and practically focused overall approach • A great deal of diversity among smart projects, initiatives, and approaches • ICT posing risks to environmental and social sustainability

Table 1.2 Shortcomings of sustainable cities

Shortcomings of sustainable cities
• A great deal of diversity among urban projects considered to be sustainable cities or districts • Diversity underneath the various usages of the term describing models of sustainable urban form • Convergence and divergence in the way urban projects conceive of what these models should be • Deficiencies in the incorporation of advanced ICT as part of sustainability solutions in conjunction with urban morphology and design features • Discrepancies between the proposed sustainability solutions and the available assessment methods • A lack of assessment frameworks for measuring the contribution of models of sustainable urban form to the goals of sustainable development • Locally or socio-culturally oriented understanding and development of sustainable cities • Difficulties in translating sustainability into the built, infrastructural, operational, and functional forms of cities • Mismatch between urban sustainability planning theory and practice • Multiple sustainability orientations, perspectives, and developmental pathways • Inconsistencies in urban strategies (design concepts and principles) through which models of sustainable urban form can be achieved • Diversity of future visions of sustainable cities • Multiplicity of performance assessment frameworks and systems for similar purposes • Versatility of different performance assessment frameworks hampering the creation of a holistic assessment framework for steering integrated sustainability challenges • Divergence in and uncertainty about what to consider and implement from the typologies and design concepts and principles of models of sustainable urban form • Urban sustainability assessment frameworks not based on simultaneous consideration of environmental, economic, and social impacts, but with a stronger focus on environmental indicators • Social goals playing second fiddle while economic goals being at the core of planning • Difficulties in making decisions and setting priorities with regard to promoting economic development, protecting the environment, and fostering social equity • Multiplicity of indicators due to the multiplicity of sustainable urban development interpretations and widely varied approaches to the operationalization of sustainable development • A lack of a systemic approach to urban sustainability to properly address the interactions between different urban components and entities • The issue of sustainable urban forms being too problematic and difficult to deal with, resulting in uncertain, different, and contradictory research results • Conception of sustainable cities in terms of forms causing inadequacy in achieving the goals ascribed to sustainable urban forms • Current models of sustainable urban form pursuing static rather than dynamic conception of urban design and planning • Diversity of models of sustainable urban form with overlaps among their visions, ideas, and concepts, creating confusion in terms of conceptualization in the field of urban sustainability • Overlaps among models of sustainable urban form complicating the implementation of typologies and design concepts and principles as planning tools • Sustainable urban forms not scalable enough in design, inefficient in functioning, and inflexible in planning in response to urban growth, environmental pressures, and changes in socioeconomic needs • Sustainable urban forms falling short in considering smart solutions in several urban domains where such solutions can have substantial contributions • A lack of agreement about the most desirable model of sustainable urban form in terms of the contribution to the goals of sustainable development

Table 1.3 Discrepancies between smart cities and sustainable cities

Discrepancies between smart cities and sustainable cities
• Sustainable cities emphasizing design concepts and principles and overlooking smart solutions, and smart cities focusing on ICT advancement and solutions efficiency and falling short in considering, if not ignore, design features • Sustainable cities striving mainly for sustainability goals and smart cities mainly for smart targets • Sustainability goals and smartness targets are misunderstood as to their synergy and interconnection • Smart cities required to incorporate the goals of sustainable development and sustainable cities to smarten up their contribution to those goals • Sustainable cities required to leverage their informational landscape and smart cities their physical landscape in line with the vision of sustainability • There is a misunderstanding of the link between the concepts of smart cities and sustainable cities • There is a weak connection between the concepts of smart cities and environmental sustainability • Smart city assessment frameworks and concepts required to be redeveloped and redefined respectively in ways that incorporate the environmental indicators and theoretical constructs of sustainable cities • Advanced technologies being used in smart cities without making any contribution to sustainability, and the strategies through which sustainable cities can be achieved being applied without considering advanced technologies

Discrepancies Between Smart Cities and Sustainable Cities

As to the weak or lack of connection between smart cities and sustainable cities, Bibri and Krogstie (2017a) provide a list of key discrepancies between these two classes of cities in the context of sustainability, as shown in Table 1.3. This is intended to stimulate scholarly inquiry into the area of smart sustainable urban development.

Key Benefits of Smart Cities and Sustainable Cities

Both smart cities and sustainable cities provide numerous benefits in terms of sustainability that should be combined and exploited in the development and implementation of smart sustainable cities of the future. Bibri and Krogstie (2017a) summarize the main advantages of smart cities and sustainable cities (see Tables 1.4 and 1.5). Regarding smart cities, the advantages are framed in connection to the current needs associated with models of sustainable urban forms.

Urban sustainability as a field of interdisciplinary research and practice has primarily focused on how to translate sustainability into urban forms and related practices through an array of design and planning concepts and principles predominantly. Yet urban analytics and development approaches are changing with ICT of the new wave of computing and its research agendas. With this move, urban researchers are realizing that concepts and approaches developed to support urban sustainability in terms of urban design and planning have become inadequate for the

Table 1.4 Main advantages of smart cities

Advantages of smart cities
• Context-aware and data-centric applications for enhancing the contribution of the typologies and design concepts of models of sustainable urban form to the goals of sustainable development • Sophisticated data-centric methods for evaluating the practicality of these typologies and design concepts as to their contribution to these goals in order to substantiate or optimize it • Data-centric techniques for comparing different models of sustainable urban form as to their contribution to those goals • Advanced models for urban design scalability, urban functioning efficiency, and urban planning flexibility necessary for responding to urban growth, environmental pressures, and changes in socioeconomic needs • Advanced tools and methods for realizing a dynamic conception of models of sustainable urban form in terms of processual outcomes of urbanization • Innovative models or frameworks for smartening up the metabolism of models of sustainable urban form to sustain their levels of sustainability • Context-aware and data-centric applications for integrating and enhancing urban systems and facilitating collaboration and coordination among urban domains in the context of models of sustainable urban form • Relating the typologies and design concepts of models of sustainable urban form to their operational functioning and planning through monitoring, automation, control, management, and optimization enabled by ICT tools • Exploring the idea of models of sustainable urban form as innovation labs using urban intelligence functions • Diversifying modeling approaches into building and aggregating urban simulation models to inform the future design of models of sustainable urban form based on forecasting or prediction capabilities • Improving participation, equity, fairness, safety, mobility, accessibility, cultural heritage, and prosperity • New ways of understanding and addressing urban problems • Identification of all kinds of urban risks, uncertainties, and hazards in models of sustainable urban form • Advancement of hard infrastructures, technologies, and social and human capital • Better management and planning of resources, infrastructures, networks, facilities, and services • Increasing collaboration among economic and societal actors and supporting innovative organizational and institutional models for advancing sustainability

Source Bibri and Krogstie (2017a)

purpose of understanding urban problems and developing solutions to support the dynamic conception of sustainable cities driven by urbanization.

The two sets of advantages are aimed at providing insights into understanding the relevance and meaningfulness of merging and harnessing the strengths of both smart cities and sustainable cities into an integrated, holistic approach into future smart sustainable urban development practices. This can be accomplished by, as one suggested solution, devising a shared framework for smartening up existing models of sustainable urban form through integrating their most sustainably sound typologies and design concepts and principles with the most advanced solutions being offered by smart cities in light of ICT of the new wave of computing in the context of sustainability (Bibri and Krogstie 2017a, b).

Table 1.5 Main advantages of sustainable cities

Advantages of sustainable cities
• Theoretically and practically grounded urban strategies for achieving the required level of sustainability • Approaches into applying the knowledge of urban sustainability and environmental technologies to the planning and design of cities • Sustainable development strategies for fostering advancement and innovation in urban infrastructures and their operational functioning, management, and planning, as well as in natural resources management • Established methods for maximizing energy efficiency, lessening pollution and waste levels, and improving human life quality and well-being • Best practices of the implementation of sustainably sound typologies and design concepts • Advanced knowledge of models of sustainable urban form in terms of different spatial levels: regional level, metropolitan level, city level, community level, neighborhood level, and building level • Different combinations of density, compactness, diversity, mixed-land use, sustainable transport, ecological design, and passive solar design, with different levels of performance of and contribution to sustainability • Successful practices of ecological diversity, green technology, integrated renewable solutions, and environmental management • Advanced frameworks for efficient metabolism • Practices of renewable energy, zero-waste, and carbon-neutral neighborhoods and districts • Environmental, social, institutional, and land use policy instruments for managing urban spaces in terms of different aspects of sustainability

Source Bibri and Krogstie (2017a)

Key Knowledge Gaps Within the Field of Smart Sustainable Cities

Since the field of smart sustainable cities is relatively new, there must be a wide range of research problems for exploration or investigation, to reiterate. Bibri and Krogstie (2017a) provide a detailed list of the existing knowledge gaps within the field of smart sustainable cities (see Table 1.6). This list includes the gaps (*italicized*) that we aim to address in this book. As for the other gaps, they constitute research avenues for future scholarly endeavors.

The intent of presenting the above knowledge gaps is to encourage scholars in the field of smart sustainable cities to discuss relevant research perspectives and to pursue diverse inquiries. In other words, the research opportunities currently available within this field are vast, including applied theoretical studies, theoretical development studies, exploratory studies, empirical studies, analytical studies, discursive and institutional studies, ethical and philosophical studies, business model innovation studies, and futuristic studies. The field is simply a fertile area of interdisciplinary scholarly research, entailing clearly a wide spectrum of explorable horizons, with many intriguing and multifaceted questions awaiting scholars and practitioners within different disciplines and fields. This is underpinned by the recognition by several research communities that the concept of smart sustainable cities holds great potential to enable urban environments to function more sustainably, safely, and efficiently than at present. Its main strength lies in the high

Table 1.6 Key knowledge gaps within the field of smart sustainable cities

Key knowledge gaps within the field of smart sustainable cities
• There is a need for applied theoretical foundations for providing an explanation and analysis of the anticipated improvement of the contribution of smart sustainable cities to sustainability prior to their development and implementation
• *There is need for integrating smart methods with the typologies and design concepts of sustainable urban forms to evaluate their practicality as to their contribution to sustainability in the context of smart sustainable cities*
• *There is a need for augmenting the typologies and design concepts of sustainable urban forms with smart applications to enhance their contribution to sustainability*
• There is no framework to be used as a classification system or ranking instrument against which smart sustainable cities can be evaluated in terms of their smart contribution to sustainability
• There is no assessment framework for measuring how smart targets can enhance sustainability goals
• Existing models are not sensitive to the needs, resources, capabilities, priorities, objectives, and wider context for individual smart sustainable cities
• There are deficiencies in the few models measuring the smartness of smart sustainable cities
• There is no common conceptual framework for comparing the evolving models of smart sustainable city and planning propositions in terms of their contribution to sustainability
• There is a need for theory for comparing the evolving models of smart sustainable city according to their contribution to sustainability goals and smart targets in an integrated approach
• There is a need for theory for evaluating the extent to which a given model of smart sustainable city contributes to sustainability as to its different dimensions
• There is a lacuna in analytical studies for testing propositions about what makes a city smart sustainable
• *There is a need for integrated frameworks for spurring the practice of the development and deployment of smart sustainable cities*
• There is no theory building in respect of the integration of sustainable city models and smart city approaches
• There is a paucity of research on conceptual and theoretical models for smart sustainable cities
• *There is no comprehensive frameworks for merging the informational and physical landscapes of smart sustainable cities to advance sustainability*
• There is a need for a holistic and shared model of smart sustainable city given the holistic and normative nature and the universal character of sustainability
• *Sustainable cities remain inadequately scalable in design and inflexible in planning without support of smart solutions considering urban growth, environmental pressures, and changes in socioeconomic needs*
• *There is a need for providing normative prescriptions for achieving the status of smart sustainable cities* and for developing assessment frameworks for measuring and improving that status
• *There is a lack of conception of sustainable urban forms in terms of processual outcomes of urbanization, which is inextricably linked to the use and application of ICT*
• Sustainable cities still focus mainly on infrastructures for urban metabolism, and fall short in considering smart solutions in several urban domains where such solutions can have a substantial contribution to different aspects of sustainability

influence it will have on many urban systems and domains in terms of sustainability and the integration of its environmental, social, and economic dimensions. This is coupled with the unique opportunity to take stock and harness the plethora of the lessons learned from more than two decades of research and planning devoted for seeking, developing, and implementing sustainable urban forms and smart city approaches, as well as how to apply this together with the most advanced ICT solutions to the challenges of sustainability and urbanization. This represents the success of the goals of sustainable development. Therefore, it is high time to leverage the theoretical and substantive knowledge accumulated hitherto on smart sustainable urban development from all kinds of previous research endeavors as well as projects and initiatives that can contribute to make urban living smarter and more sustainable—i.e., with support of ICT of the new wave of computing in terms of what it has to offer as innovative solutions and sophisticated approaches directed primarily for overcoming the challenges of sustainability and urbanization.

1.1.2.3 ICT of the New Wave of Computing: Enabling Smart Sustainable Cities of the Future

On the Urban Transformational Effects of ICT of the New Wave of Computing

As ICT has become more sophisticated and deeply embedded into the very fabric of the contemporary city, it has provided many new opportunities to make sustainable urban development work by drastically transforming the way the city functions and can be managed, planned, and developed in terms of different dimensions of sustainability as well as efficiency (e.g., Bibri and Krogstie 2016a). The new digital transition fueled by ICT of the new wave of computing and its constitutive nature, on which many cities across the globe are increasingly engaging, is projected to bring about further transformational effects. It has been widely acknowledged that technological innovations embody a morphing power in that they alter how cities evolve and reshape, and create new, urban realities. Viewing ICT as a constitutive and integrative technology represents a widening and deepening of UbiComp-, AmI-, and the IoT-, and SenComp-type approaches at the level of urban applications, to draw on Bibri (2015a). These disruptive digital technologies and their amalgamation are postulated to transform the role of ICT in the city and ultimately the way citizens live. This involves capturing further and invigorating the application demand for the urban sustainability solutions that emerging and future ICT can offer. In particular, the constitutive nature of ICT of the new wave of computing amounts to a paradigmatic change in the way the city functions, whether be it smart, sustainable, or smart sustainable. The convergence of emerging ICT will shape future cities in fundamental—and yet unexpected—ways (e.g., Shepard 2011; Batty et al. 2012; Bibri and Krogstie 2016a). This involves how they can be monitored, analyzed, probed, assessed, and planned to improve their contribution to the goals of sustainable development by relying on big data analytics and context-aware computing (Bibri and Krogstie 2017a, b). Not only is ICT seen as a critical enabler, but also as a powerful transformative driver for achieving such goals. Indeed, without ICT, the drive to improve urban systems: physical structures and spatial organizations, urban infrastructures and facilities, urban administration and governance, and ecosystem and human services, may not reach its full potential. Reaching full potential in this respect signifies new and fertile opportunities for improving urban sustainability, urban efficiency, and the quality of urban life, which ICT of the new wave of computing is well placed to instigate, provide, and sustain. Indeed, a number of smart technologies are being developed and applied to diverse urban systems and related activities and processes to conserve resources, lower pollution levels, reduce GHG emissions, streamline processes, and enhance living standards, as well as being employed to investigate and evaluate the processes of their own application, implementation, and impact on the city. The research and social practice within the area of new ICT for sustainability has a key task to fill as to urban planning and development (e.g., Rivera et al. 2015). In other words, cities entail human environments where smart solutions in line with the goals of sustainable development can be discovered, created, employed, assessed, and improved (Höjer and Wangel 2015; Bibri and Krogstie 2017a). In a nutshell, ICT can be leveraged in the advancement of sustainable development and hence in addressing the challenge of sustainability and urbanization in the context of smart sustainable cities of the future.

Technological Factors Underlying the Materialization of Smart Sustainable Cities

ICT is becoming increasingly spatially all pervasive, located anywhere and everywhere across urban environments, thereby providing the necessary basic infrastructure backbone for cities to realize their full potential as to combining sustainability and smartness. As a consequence, data sensing and information processing are being fast embedded into the very fabric of contemporary cities while wireless networks are proliferating on a hard-to-imagine scale. This has been fueled by the new digital transition in ICT enabled by various forms of pervasive of computing and driven predominantly by big data analytics and context-aware computing. This has in turn been justified by their underlying tremendous potential to enhance urban operations, functions, designs, strategies, services in line with the vision of sustainability.

Hence, the emergence and rise of the new techno-urban phenomenon of smart sustainable cities is the result of what has come to be labeled “ICT of the new wave of computing” (Bibri and Krogstie 2017a). Consequently, the prospect of smart sustainable cities is becoming the new reality with the recent advances in and integration of ICT of various forms of pervasive computing and the underlying cutting-edge enabling technologies, i.e., the massive proliferation and ubiquitous presence of data sensing, information processing, and wireless networking technologies across existing and new urban environments. Smart sustainable cities typically rely on the fulfillment of the prevalent ICT visions of the new wave of computing, where everyday objects communicate with each other and collaborate across heterogeneous and distributed computing environments to provide information and services to urbanites and diverse urban entities. Based on a thematic analysis, Bibri and Krogstie (2017b) identify four forms of pervasive computing in the urban domain: UbiComp, AmI, the IoT, and SenComp. Heralding a major technological change characterized by an ever-growing embeddedness of ICT into urban systems and domains, these socially disruptive technologies are projected to yield a drastic transformation of the techno-urban ecosystem in all its complexity and variety. This will in turn alter the way ICT can be applied and used in all urban spheres with far-reaching implications. Indeed, it has been suggested that as ICT becomes pervasive, i.e., permeate urban infrastructures, architectural designs, natural ecosystems, ecosystem services, public and social services, administrative services, governance processes, and citizens' bodies and objects, we can speak of cities getting smarter as to addressing environmental, social, and economic problems as well as providing services to citizens to improve their well-being and the quality of their life (Batty et al. 2012; Bibri and Krogstie 2017a, b; Piro et al. 2014; Shepard 2011; Townsend 2013).

The continuous rise of smart sustainable cities is opening entirely new windows of opportunity for smart cities to explicitly incorporate the goals of sustainable development and for sustainable cities to improve their contribution to the goals of sustainable development. Therefore, they are becoming increasingly powerful and established as techno-urban discourses thanks to the recent advances in several scientific and technological areas in the ambit of ICT of the new wave of computing for urban sustainability (Bibri and Krogstie 2016a) associated with context-aware computing and big data analytics and their enabling technologies, most notably intelligent embedded systems, multi-sensor data fusion and signal processing, intelligent agents/user interfaces, hybrid modeling and reasoning, machine learning, data mining, statistical analysis, situated intelligence, cloud computing, middleware infrastructure, and wireless communication protocols and networks.

Applications of ICT of the New Wave of Computing for Urban Sustainability

Significant opportunities exist for UbiComp, AmI, the IoT, and SenComp as to their amalgamation—and hence big data analytics and context-aware computing—in relation to modernizing the urban model in terms of different dimensions of sustainability, as the range of urban application areas that utilize these advanced technologies in connection with sustainability is potentially huge. In other words, such technologies usher in automation and intelligence in nearly all urban domains. Related applications include the following (Bibri and Krogstie 2016a, 2017a, b):

Significant opportunities exist for UbiComp, AmI, the IoT, and SenComp—and hence big data analytics and context-aware computing—in relation to advancing the model of smarter cities in terms of the environmental dimension of sustainability, as the range of urban application areas that utilize these advanced technologies in connection with environmental sustainability is potentially huge. In other words, such technologies usher in automation and intelligence in nearly all urban domains. Related applications include, but are not limited to, the following (Bibri and Krogstie 2016a, 2017a, b):

- Energy efficiency
- Carbon footprint reduction of the ICT industry
- Energy production, distribution, and consumption flexibility
- Industrial production processes efficiency
- Dematerialization and demobilization
- Environmental monitoring and protection
- Transport systems efficiency and management
- Water and waste management
- Water supply and distribution networks effectiveness
- Power grid management
- Low-carbon and virtual mobility
- Urban infrastructures and facilities monitoring and management
- Noise and pollution reduction
- Zero-emission and low-carbon buildings
- Natural ecosystems management
- Resource utilization efficiency
- Traffic management and street light control
- Public safety and civic security (natural disasters and environmental crisis)
- Ecosystem service provision efficiency
- Public health (air and water pollution)
- Healthcare and social support
- Learning and education
- Medical and health systems
- Urban design and land use
- Urban planning and management
- Governance and citizen participation.

There are fascinating possibilities and immense opportunities to embrace and realize from deploying and implementing the advanced solutions being offered by ICT of the new wave of computing for urban sustainability, which entails exploiting the benefits, capabilities, and innovations of big data analytics and context-aware computing to enable and advance smart sustainable cities. This can well be achieved if ICT development can be linked to the agenda of sustainable development, and ICT investment is justified by the pursuit of overcoming the challenges of sustainability and urbanization. It is conspicuous that ICT of the new wave of computing holds enormous potential to provide novel applications for addressing the environmental and socioeconomic challenges associated with sustainability and urbanization that will be facing most cities in the years ahead. Of most relevance, it is high time to marshal new urban ICT to improve the contribution of sustainable urban forms to the goals of sustainable development by pursuing smart pathways to achieve the required level of sustainability. This is due to its technological superiority that provides advanced performance and value (Bibri 2015b). However, recent studies (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a, 2017a; Böhlen and Frei 2009; Crang and Graham 2007; Kyriazis et al. 2014; Lee et al. 2008; Perera et al. 2014; Shepard 2011; Shin 2009; Thrift 2014; Zanella et al. 2014) show that most of the applications pertaining to ICT of various forms of pervasive computing, which are based on the notion of an amalgam of infrastructures, applications, and services to be directed toward improving sustainability, are still under investigation and development. This is taking place in parallel with the construction of UbiComp, AmI, the IoT, and SenComp landscapes and spaces, which is progressing on a hard-to-imagine scale across several spatial scales and spanning over diverse urban domains, not least in ecologically and technologically advanced nations.

Opportunities and Applications of Big Data Analytics and Context-Aware Computing

Big data analytics and context-aware computing provide a very rich nexus of possibilities in terms of providing support to citizens and urban entities in their activities. There has been much enthusiasm about the immense opportunities provided by new and more extensive sources of urban data to better operate, manage, plan, and develop cities to improve their contribution to the goals of sustainable development. Cities as complex systems, with their domains becoming more and more interconnected and their processes highly dynamic, rely more and more on sophisticated technologies to realize their potential for responding to the challenges of sustainability and urbanization. The most prevalent and influential of such technologies are big data analytics and context-aware computing, which are rapidly gaining momentum and generating worldwide attention in the realm of smart sustainable urban development (Bibri and Krogstie 2017a). Context-aware behavior and big data capability are considered as prerequisites for realizing the novel applications pertaining to UbiComp, AmI, SenComp, and the IoT. Specifically, big data trends are mainly associated with the IoT and UbiComp technologies and context data trends with AmI and SenComp technologies, with some overlaps among both of these trends and technologies (Bibri and Krogstie 2017a, b). The IoT is a form of UbiComp, and AmI and SenComp are two ICT visions that imply a slightly different focus in terms of the concept of context as to its elements or subsets, more specifically, AmI goes beyond the physical context to include various types of human context, such as cognitive, emotional, behavioral, social, and conversational (Bibri 2015a), which are beyond the focus of this book.

Big data is a rapidly expanding research area spanning the fields of computer science and data science, and has become a ubiquitous term in understanding and solving complex problems in different disciplinary fields, such as urban development, engineering, education, healthcare, social networks, governance, transportation, and telecommunications. The notion of big data analytics and its application in urban analytics have attracted enormous attention among urban scholars and practitioners over the past few years. The big data paradigm is fundamentally changing the way cities function and can be managed, driving decision-making in urban planning and development in the context of sustainability. It is clearly on a penetrative path across all urban systems and domains, manifested in the proliferation of big data technologies for generating, storing, managing, processing, analyzing, and sharing colossal amounts of urban data pertaining to land-use patterns, spatial organizations, environmental dynamics, socioeconomic networks, transport and traffic systems, mobility patterns, natural ecosystems, energy resources, public services, and so on. Big data hide in them the solutions to many sustainability and urbanization problems, provide raw ingredients to build tomorrow's human engineered systems, and play a key role to understand urban constituents as data agents and their behaviors and activities. Unsurprisingly, big data analytics as a general area applied to various urban domains has become of prime focus in the research field of smart sustainable cities (Bibri and Krogstie 2017a, b). Its main strength lies in the high influence it will have on many facets of smart sustainable cities and their citizens (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie, 2016b, 2017a, b; Pantelis and Aija 2013). Today, a large part of ICT investment from large technology companies like IBM, Oracle, Microsoft, SAP, and CISCO is being funneled into and directed toward how to process, analyze, manage, model, simulate, and visualize big data. In parallel, research on big data is very active in many universities and research institutions across the globe. While big data exists in every era where the tools and methods for data processing are always being stretched by increasing volumes and new varieties and velocities, the current preoccupation with big data in the realm of smart sustainable cities tends to be driven by the actual ways in which extensive data are being collected and generated automatically, routinely, and by various forms of sensors in daunting scales, increased varieties, and unprecedented velocities due to the ubiquity, complexity, and performance of sensor technologies. However, big data innovations do not simply denote a significant growth in volume, variety, and velocity, of data; rather, they denote how data are applied and exploited, and how new innovations are facilitated through big data and diffused throughout the domains of cities. In view of that, a large number of advanced big data technologies, tools, and techniques are being developed and applied in response to the urgent need for handling the complexity of urban analytics necessary for enhancing the functioning and planning of urban systems and facilitating the collaboration and coordination of urban domains in the area of smart sustainable urban development (Bibri and Krogstie 2017a, b).

Context-aware computing as a prerequisite enabling technology for ICT of the new wave of computing constitutes a key component of the infrastructure of smart sustainable cities (e.g., Bibri and Krogstie 2017a, b; Kamberov 2015; Solanas et al. 2014) and future cities (e.g., Riva et al. 2008). A smart urban environment is a set of context-sensitive systems based on pervasive computing, in which the city interacts with its citizens and components through embedded devices and sensors. Having access to context information in smart sustainable city applications plays a key role in supporting decision-making processes pertaining to sustainability (e.g., Al Nuaimi et al. 2015; Bibri and Krogstie 2017a, b; Solanas et al. 2014). It is becoming increasingly evident that smart urban environments based on context-aware technologies will be commonplace in cities in the near future to support sustainable urban living in various ways (see Bibri and Krogstie 2016a, 2017a, b). Local city governments are investing in advanced ICT to provide technological infrastructures supporting AmI and UbiComp, as well as to foster respect for the environmental and social responsibility (e.g., Solanas et al. 2014). Thus, there are many opportunities for smart sustainable cities to leverage from the use of context-aware technologies due to the role they play in several important areas, including energy, traffic, environment, education, healthcare, utility, and public safety (Bibri and Krogstie 2017a).

The use of big data analytics and context-aware computing as a set of sophisticated techniques, methods, and models offers the prospect of smart sustainable cities in which natural resources can be managed and planned safely, sustainably, and efficiently in an intelligent way to improve societal and economic outcomes. Indeed, significant opportunities exist for these two technologies in relation to transforming the sustainable urban model. The range of urban application areas that utilize big data analytics and context-aware computing in connection with the goals of sustainable development is potentially huge, as these two advanced forms of ICT usher in intelligence and automation in so many sub-domains of nearly all urban domains. Hence, the opportunities for combining big data analytics and context-aware computing technologies are enormous due to the role they will play in several important domains of smart sustainable cities of the future. As noted by Bibri and Krogstie (2016b, p. 1), "combining big data analytics and context-aware computing could be leveraged in the advancement of urban sustainability, as their effects reinforce one another as to their efforts for transforming the processes operating and organizing urban life in this direction by employing and merging data-centric and context-aware applications to enhance, harness, and integrate urban systems as well as to facilitate collaboration, coordination, and coupling among diverse urban domains." The whole idea is that the potential for the deployment of the advanced solutions being offered by ICT of the new wave of computing is tremendous in the context of urban sustainability. As noted by Bibri and Krogstie (2017a, p. 34) with reference to sustainable urban forms as instances of sustainable cities, "emerging and future ICT as a set of enabling and constitutive technologies…can make substantial contributions—not only in terms of catalyzing and boosting the…development processes of sustainable urban forms, but also in terms of planning such forms in terms of their functioning, management, and development in ways that continuously evaluate and forecast their contribution to sustainability and thus strategically advance it."

As a research direction, big data have recently attracted scholars and scientists from diverse disciplines, as well as practitioners from a variety of professional fields due to their prominence in relation to various urban domains, especially urban planning, transportation engineering, sustainable mobility, public health, and socioeconomic forecasting, in addition to being a major intellectual, scientific, and practical challenge (Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014;

Bibri and Krogstie 2017a, b). Big data analytics is increasingly seen to provide unsurpassed and innovative ways to address a range of complex environmental challenges and rising socioeconomic concerns facing contemporary cities as to the operational functioning, management, and planning of their systems. We stand at a threshold in beginning to make sense of big data technologies that will be deeply interwoven into and massively used in cities as complex and dynamic systems within the next decade. Big data analytics and its uses will play a significant role in realizing the key characteristics of smart sustainable cities, namely operation and service efficiency, life quality enhancement, natural resources optimization, and intelligent management of infrastructures and facilities. Indeed, huge expectations for gains and prospects are being placed on the ongoing research within big data in academic circles as well as in the ICT industry. Worth noting is that the big data paradigm driving the transition from smart cities and sustainable cities toward an integrated and holistic approach into urban development is in a penetrative path toward safely fueling unhindered progress on many scales and paving the way for possibly revolutionizing sustainable development engineering to achieve the long-term goals of sustainability. Therefore, big data analytics has become part of mainstream debate on sustainability and urbanization in the realm of smart sustainable cities of the future.

All in all, the management and organization of urban activities, processes, and systems in the field of sustainable urban planning and development require complex not only interdisciplinary knowledge but also sophisticated technologies and profound computational and data analytics. Big data analytics and context-aware computing capabilities hold tremendous potential to revolutionize urban analytics and computing in relation to sustainable urban planning and development. In the spirit of the evolving paradigm shift in urban planning and development, manifested in the materialization of smart sustainable cities, advances in such capabilities will make it possible to address the challenges of sustainability and urbanization in ways that were, in many cases, not conceivable, even a decade ago.

Relevant Research Gaps and Scientific and Intellectual Challenges

The bulk of work relating to the recent increase of research on big data analytics and context-aware computing in the area of urban planning and development is still characterized by scattered and small research programs and projects. This work lacks comprehensive and large-scale endeavors and initiatives. Also, while these two advanced technologies cover multiple application domains (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016b, 2017a), it is undeniable the disproportionate weight of a relatively small number of urban domains in setting the research agenda. In relation to big data analytics, many sustainability issues have not yet been effectively addressed, including public health, energy, environment, disaster forecasting, water resources, and biodiversity (DeRen et al. 2015). As to context-aware computing, this technology remains largely ignored when addressing the challenge of sustainability in smart cities and sustainable cities. In addition, there are important questions that are unexplored concerning the link between big data analytics and context-aware computing technologies for sustainability and the typologies and design concepts and principles of sustainable urban forms. These questions pertain to the key themes in debates on density, compactness, diversity, mixed-land use, sustainable transport, ecological design, and passive solar design, as well as to the ability of monitoring, probing, and planning sustainable urban forms in ways that strategically evaluate and improve their contribution to the goals of sustainable development (Bibri and Krogstie 2017b). Moreover, there are issues that are barely explored to date regarding how the urban domains operating within sustainable urban forms can be integrated into the context of big data analytics to facilitate further collaboration and coordination in terms of operations, functions, and services for advancing sustainability (see Bibri and Krogstie 2016b, 2017b).

The rising demand for big data analytics and context-aware computing as disruptive technologies, coupled with their potential to serve many urban domains in terms of sustainability, comes with major scientific and intellectual challenges that need to be addressed and overcome with regard to the design, development, and deployment of data-centric and context-aware applications in the context of smart sustainable cities. These challenges are mostly scientific, computational, and analytical in nature. They include, but are not limited to, the following (e.g., Bibri 2015a; Bibri and Krogstie 2017a, b):

- Constraints of design science and engineering
- Data management and analysis
- Database integration across urban domains
- Privacy and security
- Data growth and sharing
- Data uncertainty and incompleteness
- Data quality
- Intelligence functions and simulation models (Batty et al. 2012)
- Modeling and management of contextual information in large-scale distributed pervasive applications and in open and dynamic pervasive environments (e.g., Bettini et al. 2010; Bibri 2015a; Strimpakou et al. 2006).

The main challenges of big data analytics arise from the nature of the data being generated in terms of their large, diverse, and time-evolving character. To put it differently, the scale, heterogeneity, and velocity of urban data makes it difficult to manage, integrate, process, analyze, evaluate, and deploy. Adding to these primarily technical challenges are the financial, organizational, institutional, regulatory, and ethical ones, which are associated with the implementation, retention, and dissemination of big data across the domains and entities of smart sustainable cities. In addition, controversies over the application and benefit of big data analytics relate to limited access and related divide and ethical concerns about accessibility (Fan and Bifet 2013). Nevertheless, understanding, exploiting, and extending, or simply advancing knowledge of, the available computation, analysis, and management capabilities associated with big data analytics and context-aware computing in terms of conceptions, tools, principles, paradigms, methodologies, and risks, great opportunities could be realized in terms of improving, harnessing, and integrating urban systems and thus facilitating collaboration, coordination, and coupling among urban domains through data-centric and context-aware applications in the context of smart sustainable cities. It is safe to say that as long as big data and context data in urban analytics are driven by sustainable development agenda and thus utilized and implemented strategically for the purpose of monitoring, understanding, probing, and planning smart sustainable cities, ICT of the new wave of computing will drastically change the way such cities function as to increasing their contribution to the goals of sustainable development over the long run. This requires the current open issues stemming from the aforementioned challenges to be under rigorous investigation and scrutiny by the socio-technical systems involved in the underlying technological innovation system of big data analytics and context-aware computing, namely industry consortia, business communities, research institutes, universities, policymakers and networks, and governmental agencies.

1.2 The Aim and Objectives of the Book

Bringing together scholarly perspectives from a cross section of a number of academic and scientific disciplines and amalgamating them with significant recent technological developments of a foundational and applicable character, this book investigates the growing role and significance of ICT of the new wave of computing in advancing sustainability in the context of smart sustainable cities of the future. It provides a comprehensive overview of the blossoming, interdisciplinary field of smart sustainable cities in terms of its underlying theoretical and discursive foundations and assumptions, state-of-the-art research, up-to-date developments, research opportunities and horizons, emerging scientific trends, major global shifts, and future planning and development practices. In addition, it explores the untapped potential of big data analytics and context-aware computing as a set of advanced technologies and their novel applications to overcome the imminent challenges of sustainability and urbanization. In more detail, it examines and documents the key unexploited benefits, opportunities, capabilities, impacts, and possible routes enabled by ICT of various forms of pervasive computing (namely UbiComp, AmI, the IoT, and SenComp) in terms of enabling smart sustainable cities to strategically assess, optimize, and improve their contribution to the goals of sustainable development toward achieving sustainability and thereby containing the ramifications of urbanization. This endeavor entails a novel approach into merging the physical and informational landscapes of smart sustainable cities of the future by integrating the typologies and design concepts and principles of sustainable urban forms with the big data and context-aware technologies and their novel applications being offered by smarter cities as innovative solutions for sustainability. Further, this book identifies a number of significant challenges pertaining to, and several environmental risks posed by, ICT of the new wave of computing, as well as puts forward potential ways of overcoming and mitigating them respectively in the road ahead to attain the intended goals.

In light of the above, ICT of the new wave of computing provides the technological infrastructures, solutions, and approaches needed for advancing the contribution of sustainable urban forms to the goals of sustainable development on the basis of an effective amalgamation of big data analytics and context-aware computing in terms of the underlying core enabling technologies (namely sensor networks, data processing platforms, cloud and fog computing infrastructures, middleware architectures, and wireless communication networks) with the built environment of such forms (urban design, land use, and transportation) and their environmental and management systems. This implies looking into the application of a set of integrative elements of major theories and powerful discourses, namely urban design, urban planning, sustainable development, sustainability science, data science, computer science, complexity science; and ICT, as a foundation for future smart sustainable urban development practices. The focus is on those practices that are driven by the quest for addressing the key unsolved and unexplored issues surrounding the existing sustainable urban forms as to their contribution to sustainability with support of innovative solutions and sophisticated approaches enabled by ICT of the new wave of computing. The rationale is that the contribution of the existing models of sustainable urban form to sustainability has, over the last two decades or so, been subject to much debate, generating a growing level of criticism that essentially questions their continuous viability, reliability, and intellectual foundation.

1.3 The Motivations for the Book

The concept of smart sustainable cities is rapidly gaining momentum as both a holistic approach to urban development as well as an academic and societal pursuit, especially within ecologically and technologically advanced nations, thereby generating worldwide attention as a powerful framework for strategic sustainable development to achieve the long-term goals of sustainability. Accordingly, the motivation for this book is manifold:

- The interdisciplinary field of smart sustainable cities is fast becoming a scholarly and realist techno-urban enterprise.
- It has become of fundamental importance and high relevance to invigorate the application demand for the smart solutions for urban sustainability and its advancement that ICT—particularly big data analytics and context-aware computing as powerful enablers and drivers for the next wave of urban analytics and computing—can offer.
- To generate new ideas about and insights into enabling existing sustainable cities to realize their full potential as to improving their contribution to the goals

of sustainable development and thus achieving the required level of sustainability by getting smarter in addressing the related challenges and issues.

- To put forward novel approaches into better-translating sustainability into the built, infrastructural, operational, and functional systems of sustainable urban forms, as well as advanced analytics methods for evaluating the extent to which such forms contribute to the goals of sustainable development and how this contribution can be continuously optimized using powerful simulation models.

The underlying premise is that ICT of the new wave of computing will result in a blend of advanced solutions and sophisticated approaches enabled by constellations of instruments across many spatial scales linked via multiple networks which provide and coordinate continuous data on various urban domains in terms of the flow of decisions about the built, infrastructural, spatiotemporal, operational, functional, and socioeconomic systems of sustainable urban forms. This can provide a fertile environment conducive to catalyzing and boosting the development processes of such forms, as well as to monitoring, understanding, probing, and planning such forms in ways that strategically assess and ultimately enhance their sustainability performance thanks to the analytical power of big data, the predictive power of simulation models, and the powerfulness of intelligence functions. This constitutes an indication of the reach of the gravitational field of ICT of the new wave of computing's effort to develop novel solutions for smart sustainable cities to disentangle many of the intractable problems pertaining to sustainability and urbanization. In all, the opportunities for the development or redevelopment of sustainable urban forms through embracing advanced digital technologies and their novel applications will be enormous and rewarding with respect to sustainability and urbanization.

1.4 The Structure of the Book and Its Contents

The book is divided into eleven (11) chapters. Opening the book as a scene-setting chapter, this chapter provides a detailed introduction: background, literature review, aim and objectives, and motivations, as well as the structure of the book and its contents. This thorough introductory chapter, as a by-product of its intent, consists in a comprehensive overview of the blossoming interdisciplinary field of smart sustainable cities in terms of its underlying theoretical and discursive foundations and assumptions, state-of-the-art research, up-to-date developments, research opportunities and horizons, emerging scientific trends, major global shifts, and future planning and development practices. The relevant topics, questions, and knowledge gaps pointing to a need for meaningful and deliberate investigation are introduced in this chapter, and will be developed further, analyzed, evaluated, and discussed in the subsequent chapters as part of the systematic exploration of the subject of smart sustainable cities of the future.

Chapter 2 endeavors to systematize the very complex and dense scientific area of smart sustainable cities in terms of identifying, distilling, and structuring the core dimensions of a foundational framework for smart sustainable city development as a set of future practices. In doing so, it focuses on a number of fundamental concepts and theories along with academic disciplines and discourses, with the aim of setting a framework that analytically relates city development, sustainability, and ICT, while emphasizing how and to what extent sustainability and ICT have particularly become influential in city development in modern society. This chapter provides an important lens through which to understand a set of influential theories and established academic disciplines and discourses of high integration, fusion, and applicability potential in relation to the practice of smart sustainable city development.

Chapter 3 reviews and synthesizes the relevant literature with the objective of identifying and distilling the core enabling technologies of big data analytics and context-aware computing as ecosystems in relevance to smart sustainable cities, as well as illustrates the key computational and analytical techniques and processes associated with the functioning of such ecosystems. In doing so, we develop, elucidate, and evaluate the most relevant frameworks pertaining to big data analytics and context-aware computing in the context of smart sustainable cities, bringing together research directed at a more conceptual, analytical, and overarching level to stimulate new ways of investigating their role in advancing urban sustainability. In terms of originality, a review and synthesis of the technical literature have not been undertaken to date in the urban literature, and in doing so, we provide a basis for urban researchers to draw on a set of conceptual frameworks in future research. The proposed frameworks, which can be replicated and tested in empirical research, will add additional depth and rigor to studies in the field.

Chapter 4 is about thinking data-analytically about urban sustainability problems, which is aided by conceptual frameworks as processes with well-defined stages to help structure and systematize urban data-analytic thinking. Specifically, it aims to synthesize, illustrate, and discuss a systematic framework for urban (sustainability) analytics based on cross–industry standard process for data mining in response to the emerging wave of city analytics in the context of smart sustainable cities.

Chapter 5 examines the real potential of big data and data-driven decision-making for revolutionizing or transforming the process of planning for the purpose of achieving the goals of sustainable development in the context of smart sustainable cities, focusing on different dimensions and functions of planning as well as their synergy and integration.

The purpose of Chapter 6 is twofold. Grounded in systems theory as one of the sciences of complexity, this chapter endeavors to systematically explore the key underlying structures, behavioral patterns, conditions, relationships, and interactions of smart sustainable cities as complex systems, and to elucidate the related principles in terms of methods, mechanisms, and goals. The intent of offering the knowledge to describe and analyze such systems accordingly is to surface noteworthy relationships as well as their implications for sustainability so as to provoke thought, foster deeper understanding, and create fertile insights, with the primary purpose of making visible possible places for actions that improve the contribution of smart sustainable cities to the goals of sustainable development toward sustainability. This can be accomplished by means of devising powerful urban intelligence functions and robust urban simulation models for strategic decision-making based on big data analytics, coupled with urban design concepts and planning principles of sustainability. Accordingly, this chapter also discusses the potential of big data analytics and related urban intelligence functions and urban simulation models in catalyzing and boosting the strategic process of sustainable development by providing more innovative solutions for monitoring, managing, planning, and designing smart sustainable cities of the future.

Chapter 7 has a twofold aim. First, it intends to examine and substantiate the potential of big data analytics and context-aware computing to improve urban sustainability. This entails integrating the big data and context-aware applications of emerging smart sustainable cities with the typologies and design concepts of sustainable urban forms to achieve multiple hitherto unrealized smart sustainable targets, or in ways that intelligently improve the contribution of sustainable urban forms to the goals of sustainable development. In doing so, we offer a conceptual framework in the form of a matrix of smart sustainable urban form to help planners and scholars in understanding and analyzing how the contribution of such form to sustainability can be improved with support of advanced forms of ICT. Second, this chapter explores the opportunity of merging the physical and informational landscapes of smart sustainable cities to achieve the goals of sustainable development. Accordingly, two analytical frameworks are proposed, in which the components of the physical landscape of sustainable urban forms and those of the informational landscape of smart sustainable cities are identified on the basis of a thematic analysis and then merged together to enable and support data-centric and context-aware applications across urban systems and domains in the context of sustainability. Specifically, the study identifies two most influential technologies and their novel applications pertaining to models of smart sustainable city as well as three design concepts and four typologies related to models of sustainable urban form.

Chapter 8 explores urban and ICT project and related risk management in the context of smart sustainable cities, as well as the various models of governance of their functioning and development. The emphasis in risk management is placed on both urban development and ICT projects as well as information security in relation to the use of cloud computing as an increasingly widely applied solution for big data analytics and context-aware applications. As to governance models, we put emphasis on poly-centric, participatory, and big data governance. This is deemed of particular importance to providing insights into workable, practice-oriented solutions for the management of the complexity of smart sustainable cities increasingly being sought by urban planners, strategists, policymakers, and decision makers.

Chapter 9 explores and reviews the real potential of big data analytics and context-aware computing for improving sustainability in the context of smart sustainable cities. In doing so, it enumerates, describes, and discusses the state-of-the-art data-centric and context-aware applications pertaining to diverse urban systems and domains, as well as identifies the key challenges involved and discusses the open issues stemming from these challenges.

The aim of Chapter 10 is manifold. First, it reviews the key deficiencies, misunderstandings, fallacies, and challenges associated with smart and smarter cities with respect to environmental sustainability. Second, it identifies the significant risks that smarter cities pose to environmental sustainability, which are expected to escalate during the transition of smart cities to smarter cities. Third, it substantiates the potential that smarter cities hold in accelerating and advancing environmental sustainability on the basis of ICT of various forms of pervasive computing. The underlying assumption is that smarter cities are still at the early stage of their development and thus could, if planned strategically, do a lot more in this regard, including the mitigation of environmental risks posed by ICT itself, if linked to the goal of environmentally sustainable development. Fourth, this chapter endeavors to reflect on what it means for smart cities to move behind their foundational visions as they transition to smarter cities and embrace environmental sustainability as an important trend increasingly gaining prominence in urban development as a result of the unprecedented urbanization of the world. Fifth, it probes both the ways in which the transition of smart cities to smarter cities (with environmental sustainability in mind) can be managed or governed at the macro level as well as the role of politics and policy in the creation and evolution of smarter cities. This entails drawing on different theoretical perspectives from socio-technical studies, innovation studies, and discursive studies, most notably transition governance; technological and national innovation systems; and the link between political practice and the emergence, insertion, and functioning of new discourses.

Chapter 11 aims to provide a comparative account of the most commonly applied approaches in futures studies dealing with technology and sustainability (forecasting and backcasting); to review the existing backcasting methodologies and discuss the relevance of their use in terms of their steps and guiding questions in analyzing strategic smart sustainable city development as an area that is at the intersection of city development, sustainable development, and technology development; to synthesize a backcasting approach based on the outcome of the review and discussion, and to examine backcasting as a scholarly methodology and planning approach by looking at its use in the Gothenburg 2050 Project and an ongoing PhD project, as well as to use these cases to illustrate the core and relevance of the synthesized approach. Backcasting is a special kind of scenario methodology to develop future models for smart sustainable city as a planning tool for urban sustainability. Goal–oriented backcasting approaches declare long–range targets that lie quite far in the future. Visionary images of a long–term future can stimulate an accelerated movement towards achieving the goals of urban sustainability.

Chapters 3–11 have a standardized scholastic structure making them easy to navigate. That is, these chapters are presented and organized in a form of journal articles encompassing abstract, introduction, analysis and discussion, and conclusions and implications. As to the conceptual, theoretical, and discursive background underpinning these chapters, it is covered in a separate chapter (2) for organizational purposes. This chapter provides a detailed introduction to the book.

By and large, this book is about the extraction of useful knowledge from large masses of data and the inference of context knowledge from huge amounts of sensor data for the purpose of enhancing and supporting decision-making in relation to the operational functioning, management, and planning of smart sustainable cities of the future. As the massive collection of data has spread through just about every domain of both smart cities and sustainable cities, so have the opportunities for data mining and information processing. Underlying the extensive body of techniques for mining data and processing contextual information is a much smaller set of fundamental concepts comprising data science and computer science respectively. These concepts are general and encapsulate much of the essence of data mining and contextual information processing in relation to urban analytics. Success in today's data-driven and context-aware urban environments entails the ability to think about how these fundamental concepts apply to particular urban sustainability problems—to think big data-analytically and context-data computationally. The premise is that big data and context data should be thought of as an asset in the realm of smart sustainable cities, a direction of thinking that brings the fundamental question of how much current smart cities and sustainable cities should invest in big data and context data. Thus, an understanding of these fundamental concepts is especially important for any one directing the application of analytics in one of the urban domains that are associated with some dimension of sustainability. There is convincing evidence that data-driven and context-aware decision-making and related technologies substantially improve sustainability performance with respect to urban operations, functions, services, designs, strategies, practices, and policies, depending on the relevance of big data and context-aware applications. As to big data and context-aware technologies, in 15 years' time the predominant computational algorithms, analytical techniques, and data processing platforms will likely have advanced enough that a detailed discussion in this book would be obsolete, while the general principles are the same as they were 20 or so years ago, and likely will change little over the coming decades. Besides, there are so many books out there that cover computational algorithms, analytical techniques, and data processing platforms in more detail with illustrative examples for the reader interested in exploring the field of big data and context-aware computing further, whether in relation to city or other venues.

The contents of this book are organized to achieve two main outcomes. Firstly, it is written so that the reader can read it easily from end to end. Although it is not an overly long book, it is packed with value to various classes of readers. Whether the reader diligently sits down and reads it in a few sessions at home/the library or go through a little every now and then, he/she will find it interesting to read and accessible—especially those readers with passionate interest in smart and sustainable cities or with deep curiosity about socially disruptive technologies and their far-reaching societal implications. Secondly, it is written so that the reader can call upon specific parts of its information in an easy manner. Furthermore, each of its chapters can be read on its own or in sequence. It is difficult to assign a priority rating to the chapters given that the book is intended for readers with different backgrounds and interests, but the reader will get the most benefit from reading the whole book in the order it is written so that he/she can gain a better understanding of smart sustainable cities as a holistic urban development approach and interdisciplinary field. However, if the reader is short of time and must prioritize, he/she can start with those chapters he/she finds of highest priority based on his/her needs, desires, or interests. Hence, as to how important or relevant the topics are, the choice is yours—based on your own evaluation. Lastly, not infrequently I have been asked by my colleagues and some professionals of different backgrounds to recommend them some book on smart sustainable cities which shall be reasonably short, well illustrated without being very costly, and not too hard to understand.

Overall, the book has been carefully designed to provide you with the tools, material, and repository required to explore the realm of smart sustainable cities, which are extremely complex, dynamic, and powerful ecosystems. Hence, they are well worth exploring in some depth and from multiple disciplinary perspectives. The best way to enable the reader to embark on such exploration is to amalgamate technological, scientific, urban, social, and environmental perspectives in a multifaceted, unified analysis and evaluation. Achieving such amalgamation in a form of a systematic examination is the main strength and major merit of this book. And succeeding in doing so is meant to provide the reader with valuable insights into the imminent technological innovations and their anticipated role in, and implications for, enabling smart sustainable cities of the future, coupled with potential ways of how to rise to the associated challenges in terms of sustainability and urbanization. Adding to this is to offer people of technologically and ecologically advanced nations the resources with which to evaluate the opportunities for smart sustainable cities to win the battle of sustainability and tackle the challenge of urbanization in the years ahead. This is believed to be an important achievement in its own right, and certainly makes the book a rewarding reading and learning experience for anyone who feels they could benefit from and leverage a greater understanding of the domain of smart sustainable urban planning and development. I encourage the reader to make the most of this opportunity to explore smart sustainable cities as an inspiring and yet contested techno-urban vision of the future. While some of us might shy away from foreseeing what the future urban world will look like, it is certain to be a very different world. I wish you well on the exploration journey.

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Chapter 2
Conceptual, Theoretical, Disciplinary, and Discursive Foundations: A Multidimensional Framework

Abstract In the subject of smart sustainable cities, the underlying theories are a foundation for practice. Moreover, scholarly research in the field of smart sustainable cities operates out of the understanding that advances in the underlying knowledge necessitate pursuing multifaceted questions that can only be resolved from the vantage point of interdisciplinarity or transdisciplinarity. Indeed, research problems in this field are inherently too complex to be addressed by single disciplines. In addition, since the area of smart sustainable cities is not a specific direction of research, it does not have a unitary framework in terms of a uniform set of concepts and theories. Indeed, it represents multiple, diverse research directions and thus various inquiry approaches, including theoretical, applied theoretical, exploratory, empirical, and futuristic. These may be analytically quite diverse. The approach to this scholarly endeavor is of an applied theoretical kind, and its aim is to investigate and analyze how to assess, advance, and sustain the contribution of sustainable urban forms to the goals of sustainable development with support of ICT of pervasive computing under what is labeled "smart sustainable cities of the future." This involves the application of a set of integrative foundational elements drawn from urban planning, urban design, sustainability, sustainable development, sustainability science, data science, computer science, complexity science, and ICT. Accordingly, it is deemed of high significance to devise a multidimensional framework consisting of relevant concepts, theories, and academic disciplines and discourses that underpin the development of smart sustainable cities as a set of future practices. This framework in turn emphasizes the interdisciplinary and transdisciplinary nature and orientation of the topic of smart sustainable cities and thus the relevance of pursuing an interdisciplinary and transdisciplinary approach into studying this topic. Therefore, this chapter endeavors to systematize the very complex and dense scientific area of smart sustainable cities in terms of identifying, distilling, and structuring the core dimensions of a foundational framework for smart sustainable city development as a set of future practices. In doing so, it focuses on a number of fundamental concepts and theories along with academic disciplines and discourses, with the aim of setting a framework that analytically relates city development, sustainability, and ICT, while emphasizing how and to what extent sustainability and ICT have particularly become influential in city

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development in modern society. This chapter provides an important lens through which to understand a set of influential theories and established academic disciplines and discourses with high integration, fusion, and applicability potential in relation to the practice of smart sustainable city development.

Keywords Smart sustainable cities · Theory · Discipline · Discourse
Science · Interdisciplinarity · Transdisciplinarity · Sustainability
Sustainable development · Computing · ICT

2.1 Introduction

In the subject of smart sustainable city development, the underlying theories constitute a foundation for action—urban practices. For example, the theories of sustainability and ICT have become influential in many aspects of urban life, whether in the built environment, urban systems, urban domains, urban services, or urban forms. The main premise is that the development of smart sustainable cities as a form of practice is undermined by complex interdisciplinary and transdisciplinary knowledge. In more detail, smart sustainable cities as a holistic urban development approach involves a range of theoretical perspectives and scientific and technological foundations drawn from a variety of academic disciplines and discourses converging on a common techno-urban vision of the future and the immense opportunities and fascinating possibilities such future will bring that are created by amalgamating innovative solutions and sophisticated approaches enabled by ICT of pervasive computing with design concepts and planning principles of sustainable urban forms (Bibri and Krogstie 2016a, 2017b).

Furthermore, scholarly research in the field of smart sustainable cities operates out of the understanding that advances in the underlying knowledge necessitate pursuing multifaceted questions that can only be resolved from the vantage point of interdisciplinarity or transdisciplinarity. Research problems in this field are indeed inherently too complex to be addressed by single disciplines, thereby the appropriateness of espousing an interdisciplinary or transdisciplinary approach to the study of smart sustainable city development. This pertains to the world's most pressing problems with long-term wide-area impact (Max-Neef 2005). The growing interdisciplinary movement in scholarly research continues to seek a holistic understanding of phenomena in the pursuit of a common purpose or task. Interdisciplinarity involves the integration of two or more academic disciplines into research endeavors. Urban sustainability requires understanding of diverse academic disciplines to solve complex problems. Interdisciplinarity can best be applied to complex subjects that can only be understood by combining the perspectives of two or more academic disciplines. An interdisciplinary field is an organizational unit that crosses boundaries between academic disciplines, as new needs emerge. Seeking to provide a holistic understanding of the techno-urban phenomenon of smart sustainable cities for the purpose of policy or in the pursuit of normative actions associated with implementing sustainability, the interdisciplinary approach insists on the mixing of academic disciplines. Thereby, it crosses boundaries between such disciplines to create new perspectives and insights based on interactional knowledge beyond these disciplines. To put it differently, interdisciplinarity is about creating something new by thinking across boundaries. Its prominence lies in that it enables to interlink different analyses and spill over disciplinary boundaries to achieve a deeper level of understanding and thus enhance practices. However, multidisciplinary efforts remain limited in impact on theory building for coping with the changing human condition (Morinière 2012).

Whereas a transdisciplinary movement insists on the fusion, rather than the mixing, of academic disciplines with a result that exceeds the simple sum of each (e.g., Lawrence and Després 2004). Transdisciplinarity lends itself most readily to the exploration of complex problems. Transdisciplinary research denotes research efforts conducted in light of different academic disciplines in a joint endeavor to create new conceptual, theoretical, and methodological innovations that integrate and move beyond discipline-specific approaches to address a common problem. Transdisciplinarity concerns that which is at once between the disciplines, across the different disciplines, and beyond each individual discipline. Its goal is the understanding of the present world, of which one of the imperatives is the overarching unity of knowledge. Aiming for a transdisciplinary perspective, the analysis in this scholarly work draws on several theories and academic disciplines and discourses. Understanding the tenets of many pertinent theories permits a more complete understanding of the development of smart sustainable cities as a set of future practices. Starting with the most holistic, these theories are drawn from urban design, urban planning, sustainability, sustainable development, sustainability science, data science, computer science, complexity science, systems thinking, systems theory, and ICT. The intent is to set side-by-side elements of a few theories that have clear implications for the development of smart sustainable cities of the future. In this field, the tension is between scientific, environmental, social, institutional, and political practices and the development and performance of urban systems and technological applications.

In light of this, it is deemed of high significance to devise a multidimensional framework consisting of relevant theories and academic disciplines and discourses that underpin the development of smart sustainable cities as a set of future practices. This framework in turn highlights the interdisciplinary and transdisciplinary nature and orientation of the topic of smart sustainable cities and thus the relevance of pursuing an interdisciplinary and transdisciplinary approach into studying this topic. Therefore, this chapter endeavors to systematize the very complex and dense scientific area of smart sustainable cities in terms of identifying, distilling, and structuring the core dimensions of a foundational framework for smart sustainable city development as a set of future practices. In doing so, it focuses on a number of fundamental theories along with academic disciplines and discourses, with the aim of setting a framework that analytically relates city development, sustainability, and ICT, while emphasizing how and to what extent sustainability and ICT have particularly become influential in city development in modern society.

The remainder of this chapter is organized as follows. Section 2.2 addresses the conceptual and theoretical dimension of the foundational framework for smart sustainable city development. Section 2.3 looks at the disciplinary dimension of the foundational framework for smart sustainable city development. Section 2.4 delves into the discursive dimension of the foundational framework for smart sustainable city development. This chapter ends, in Sect. 2.5, with concluding remarks along with some reflections.

2.2 The Conceptual and Theoretical Dimension of the Foundational Framework for Smart Sustainable City Development

2.2.1 Concepts and Theories

The underlying theories are a foundation for smart sustainable city development as a set of practices. In this section, we shall describe and discuss the key constructs that constitute the conceptual and theoretical framework for this scholarly work. Moreover, we shall succinctly highlight and illustrate important linkages between such constructs in the context of smart sustainable cities of the future.

2.2.1.1 Smart Cities

There are different views regarding the origin of the concept "smart city" in the literature. According to Gabrys (2014), the roots of the concept date back to the 1960s under what is called the "cybernetically planned cities," and in urban development plans, it has figured in proposals for networked cities since the 1980s. Dameri and Cocchia (2013) claim that the concept was introduced in 1994. Neirotti et al. (2014) state that the origin of the concept can be traced back to the smart growth movement in the late 1990s. Batty et al. (2012) confirm that it is only until recently that the concept has been adopted in city planning through the movement of smart growth. Speaking of which, it entails increasing urban efficiency with regard to energy, transportation, land use, communication, economic development, service delivery, and so forth. Indeed, a smart city represents essentially efficiency, which is based on intelligent management of urban systems using ICT. Further, it is the period after the emergence of smart city projects supported by the European Union since 2010 that has witnessed a proliferation of writings and academic publications on the topic of smart city (Jucevicius et al. 2014).

Nowadays, smart city is a catchphrase that draws increased attention among research institutes, universities, governments, policymakers, and ICT companies. Notwithstanding the wide use of the concept today, there is still unclear and inconsistent understanding of its meaning (e.g., Ahvenniemi et al. 2017; Al Nuaimi et al. 2015; Angelidou 2015; Batty et al. 2012; Caragliu et al. 2009; Chourabi et al. 2012; Khan et al. 2015; Marsal-Llacuna et al. 2015; Neirotti et al. 2014; Song et al. 2017; Wall and Stravlopoulos 2016). In view of that, a great number of definitions have been suggested different emphases, although academics, ICT experts, and policymakers converge on the use of ICT across all domains of smart cities, and hence on considering it as an inseparable facet thereof. A wide variety of smart city definitions are available (Albino et al. 2015). In addition, smart city has many faces that tend to vary on the basis of such aspects as the way ICT is applied, the digital means by which it is coordinated and integrated, the extensiveness of its use, and the degree of its pervasiveness. These faces include virtual cities, cyber cities, digital cities, networked cities, intelligent cities, knowledge cities, and real-time cities, among many other nomenclatures, as well as hybrid cities which combine two or more of these names. Adding to these cities are the ones that are inspired by ICT of various forms of pervasive computing, such as ubiquitous cities, ambient cities, sentient cities, and cities as Internet-of-everything (e.g., Böhlen and Frei 2009; Crang and Graham 2007; Kyriazis et al. 2014; Perera et al. 2014; Lee et al. 2008; Shepard 2011; Shin 2009; Thrift 2014; Zanella et al. 2014). These cities are the object of the next subsection. However, common to all smart cities as urban development strategies or approaches is the idea that ICT is, and will be for many years to come, central to urban operations, functions, services, and designs

There is no canonical or universally agreed upon definition of smart city. It is a difficult concept to pin down or strictly delineate, and can still be considered a vague notion. A shared definition of smart city is not available, and it is hard to identify common trends at global level (Neirotti et al. 2014). The concept tends overall to be context-dependent—i.e., diverse smart city projects, initiatives, and endeavors are based on particular target objectives, available resources, financial capabilities, regulatory and policy frameworks, political structures, and so on. It also depends on the state-of-the-art research and development in the field of ICT as to the available solutions with respect to architectures, technologies, applications, systems, models, methods, computational analytics, and so forth. As an example of target objectives, Batty et al. (2012) identify a number of projects pertaining to smart cities of the future, including mobility and travel behavior; modeling urban land use; integrated databases across urban domains; sensing, networking, and the impact of social media; participatory governance and planning structures; modeling network performance; transport and economic interactions; and decision support as urban intelligence. As regards to the financial capabilities, the growing interest in the concept of smart city, driven by the needs to address and solve urbanization challenges, has led to several investments in ICT development and deployment manifested in the high number of jointly funded research endeavors as well as smart city initiatives and implementation projects (Ahvenniemi et al. 2017). In all, it is evident that smart city lacks a shared definition, and thus, it is hard to identify common trends.

In essence, there are two mainstream approaches to smart city: (1) the technology and ICT-oriented approach and (2) the people-oriented approach, i.e., stakeholders, knowledge, services, and even data. Specifically, there are smart city strategies which focus on the efficiency and advancement of hard infrastructure and technology (transport, energy, communication, waste, water, etc.) through ICT, and strategies which focus on the soft infrastructure and people, i.e., social and human capital in terms of knowledge, participation, equity, safety, and so forth (Angelidou 2014). As an example of the first approach, Kitchin (2014) conceives of smart city as one that monitors and integrates all of its critical infrastructures, optimizes its resources, plans its activities, and maximizes services. In this line of thinking, Marsal-Llacuna et al. (2015) state that by using ICT and data analytics technologies, smart cities aim to monitor and optimize existing infrastructure, to increase collaboration among economic actors, to provide more efficient services to citizens, and to support innovative business models across private and public sectors. As to the second approach, Neirotti et al. (2014) describe smart city as a way of enhancing the life quality of citizens. Smart city entails human and social factors, apart from physical and technological factors (Aguilera et al. 2013). Lombardi et al. (2011) emphasize additional soft factors such as participation, safety, and cultural heritage. Other views tend to put emphasis on services (e.g., Belanche et al. 2016; Lee et al. 2014). Belanche et al. (2016) underscore the increased use of urban services to attain efficiency and sustainability. Angelidou (2014) underscores the role of ICT to achieve prosperity, effectiveness, and competitiveness. The interested reader might want to read a recent book by Song et al. (2017) to gain a broad understanding of the concept of smart cities. The authors provide a detailed account on the foundations, principles, and applications of smart cities.

It is important to highlight the body of the literature focusing on the role of human and social capital, in addition to new technologies, in developing smart cities that aim to improve economic, social, and environmental sustainability (e.g., Anthopoulos 2017; Batty et al. 2012; Giffinger et al. 2007; Hollands 2008; Nam and Pardo 2011; Neirotti et al. 2014). This stream of literature is concerned with smart cities as urban innovations based on ICT that aims at harnessing physical and social infrastructures as well as natural and knowledge resources for economic regeneration, environmental efficiency, and public and social service enhancement. One of the most cited definitions in this regard is the one advanced by Caragliu et al. (2009, p. 6), which states that a city is smart "when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance." This definition is based on a model that has been used as a classification system—developed through six distinct dimensions, namely, smart mobility, smart environment, smart living, smart people, smart economy, and smart governance—against which smart cities can be gauged or evaluated in terms of their development in the direction of smartness. This model is said to represent a holistic understanding by what it entails in terms of the complementary nature of these dimensions. Though it does not provide a prioritization of these dimensions as to their contribution to sustainability, nor does it specify how they can add to urban development and planning practice in terms of sustainability. Nevertheless, this connotation of smart city is seen as a strategic device to highlight the growing role and potential of ICT in enabling and catalyzing sustainable urban development processes. Indeed, it goes beyond technological investments and advancements to include environmental, social, and economic developments with sustainability in mind. In extending this definition, Pérez-Martínez et al. (2013, cited in Ahvenniemi et al. 2017) describe smart cities as "cities strongly founded on ICT that invest in human and social capital to improve the quality of life of their citizens by fostering economic growth, participatory governance, wise management of resources, sustainability, and efficient mobility, whilst they guarantee the privacy and security of the citizens." In a similar vein, Batty et al. (2012, pp. 481–482) conceive of smart cities as cities "in which ICT is merged with traditional infrastructures, coordinated and integrated using new digital technologies," and where "intelligence functions…are able to integrate and synthesize…[urban] data to some purpose, ways of improving the efficiency, equity, sustainability, and quality of life in cities." In all, smart cities endeavor to amalgamate advanced digital technologies and urban planning approaches to find innovative and smart solutions that contribute to improving livability and enhancing sustainability (see Toppeta 2010). Smart initiatives can be used to promote environmental sustainability (Kramers et al. 2014). This implies that sustainability is not an integral part of all the definitions of smart city.

In all, there are several commonalities and differences among the existing definitions of smart city. This implies that these definitions converge on some aspects and diverge on others, including social, cultural, economic, environmental, physical, technological, political, institutional, and futuristic, in addition to sustainability, equity, and policy. To provide the most comprehensive definition of smart city in light of the above analytical account means adopting a more generic view that puts together the core aspects of smart city as a very broad concept, which involves a set of intertwined societal factors. With that in regard, a smart city is a city that badges, or is striving to regenerate, itself as smart in terms of efficiency, sustainability, equity, and livability by advancing and integrating the physical infrastructure, the ICT infrastructure, the social infrastructure, and the economic infrastructure to leverage the collective intelligence of the city. It is an innovative city that focuses on applying the next-generation ICT to all walks of life and hence performs in a forward-looking and participatory way in governance, economy, people, mobility, environment, and living on the basis of the intelligent combination of endowments and activities of independent and aware citizens to ensure socioeconomic development, the quality of life, the intelligent management of natural resources, and the efficient operation of infrastructures and facilities.

2.2.1.2 Smarter Cities

The increasing convergence, prevalence, and advance of urban ICT is giving rise to new faces of cities that are quite different from what has been experienced hitherto on many scales. These cities are labeled "smarter cities" because of the magnitude of ICT and the profusion of data as to their embeddedness and use in urban systems and domains. The prospect of smart cities getting smarter is becoming the new reality with the massive proliferation of the core enabling technologies underlying ICT of the new wave of computing, namely, data sensing systems, cloud/fog computing infrastructures, data processing platforms, middleware architectures, and wireless communication networks across various spatial scales. Smarter cities include ubiquitous cities (e.g., Batty et al. 2012; Lee et al. 2008; Shin 2009), ambient cities (e.g., Böhlen and Frei 2009; Crang and Graham 2007), sentient cities (e.g., Shepard 2011; Thrift 2014); cities as Internet-of-everything (e.g., Kyriazis et al. 2014; Perera et al. 2014; Zanella et al. 2014), and real-time cities (e.g., Batty et al. 2012; Kitchin 2014). They are seen as future forms of smart cities. The initiatives of smarter cities enabled by ICT of various forms of pervasive computing (namely, UbiComp, AmI, SenComp, and the IoT) in several countries across Europe, the USA, and Asia are increasingly considered as national urban development projects that center on strengthening the role of ICT, especially big data analytics and context-aware computing, in urban operations, functions, services, and designs as to management, planning, and development to advance urban sustainability, among other things.

In light of the above, the concept of smarter cities is built upon the core characteristic features of the prevalent ICT visions in terms of the ubiquity of computing in urban systems, massive use of ICT in urban domains, and its numerous benefits and opportunities for cities and citizens. That is, the pervasion of sensors technologies, information processing systems, and computational analytics and communication capabilities into urban environments and thereby the omnipresence and always-on interconnection of computing resources and services across many spatial and temporal scales. Accordingly, the conceptualization of smarter cities is associated with the ever-growing and deep embeddedness of advanced ICT into the very fabric of the city in terms of operations, functions, designs, and services. It indeed differentiates smarter cities as emerging and future cities from the aforementioned conceptualizations of common smart cities. In this respect, Townsend (2013, p. 15) defines a smart city as an urban environment where ICT “is combined with infrastructure, architecture, everyday objects, and even our own bodies to address social, economic and environmental problems.” Piro et al. (2014, p. 169) describe it “as an urban environment which, supported by pervasive ICT systems, is able to offer advanced and innovative services to citizens in order to improve the overall quality of their life.” According to Su et al. (2011), a smart city mainly focuses on embedding the next-generation of ICT into every conceivable object or all walks of life, including roads, railways, bridges, tunnels, water systems, buildings, appliances, hospitals, and power grids, in every corner of the world, and constituting the IoT. Chourabi et al. (2012) define a smart city as a city which strives to become smarter in the sense of making itself more efficient, livable, equitable, and sustainable. Here, the word “smarter” implies the use of advanced ICT in order to improve efficiency, sustainability, equity, and the quality of life. This is in line with what constitutes smart cities of the future according to Batty et al. (2012). The basic idea is that future smart cities have greater potential than existing smart cities for advancing their contribution to the goals of sustainable development. This is due to the current capabilities as well as the prospective advancements pertaining to big data analytics and context-aware computing as advanced forms of ICT, in addition to their increasing amalgamation in various urban domains and systems in terms of the underlying core enabling technologies, namely, sensor devices, computing infrastructures, data processing platforms, and wireless communication networks (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016b, 2017b; Böhlen and Frei 2009; DeRen et al. 2015; Kamberov 2015; Khan et al. 2014, 2015; Shepard 2011; Solanas et al. 2014). In all, a smarter city can be described as a city where advanced ICT is combined with physical, infrastructural, architectural, operational, functional, and ecological systems across many spatial scales, as well as with urban planning approaches, with the aim of improving efficiency, sustainability, equity, and livability. Smarter cities entail that diverse context-aware and big data applications operating across cloud computing infrastructures can monitor what is happening in urban environments (in terms of situations, events, activities, behaviors, locations, spatiotemporal settings, environmental states, socioeconomic states, and so on) and process, analyze, interpret, visualize, and react to the outcome through decision support systems and strategies at varying ways—be it in relation to smart energy, smart grid, smart street and traffic lights, smart transport, smart mobility, smart health care, smart education, smart safety, smart planning, smart governance, or smart buildings—across many spatial scales (Bibri and Krogstie 2016b). Here, smartness should primarily be focused on the goals of sustainable development rather than on only technology and the efficiency of smart solutions. There has been a shift in cities striving for smartness targets instead of sustainability goals (Marsal-Llacuna et al. 2015).

2.2.1.3 Sustainable Cities—Sustainable Urban Forms

There are various definitions of what a sustainable city should be. Based on the literature on compact city, eco-city, and new urbanism as the most prevalent and sustainable models of sustainable urban form as instances of sustainable city (e.g., Bohl 2000; Hofstad 2012; Jabareen 2006; Jenks et al. 1996a, b; Joss 2010; Girardet 2008; Rapoport and Vernay 2011; Williams 2009), a sustainable city can be understood as a set of approaches into practically applying the knowledge of urban sustainability and related technologies to the planning and design of existing and new cities or districts. In the context of this chapter, a sustainable city can be described as an urban environment designed with the primary aim of contributing to improved environmental quality and protection and social equity and well-being over the long run, which can be attained through adopting sustainable development strategies to foster advancement and innovation in built environment, infrastructure, operational functioning, planning, and ecosystem and human service provisioning, while continuously optimizing efficiency gains. In more detail, sustainable cities strive to maximize efficiency of energy and material resources, create a zero-waste system, support renewable energy production and consumption, promote carbon neutrality and reduce pollution, decrease transport needs and encourage walking and cycling, provide efficient and sustainable transport, preserve ecosystems, emphasize design scalability and spatial proximity, and promote livability and sustainable community.

Sustainability has become an increasingly important concept not just in politics, but also in research and planning. Sustainable development has consequently had a significant impact on the development of modern cities in terms of different dimensions of design and planning in line with the goals of sustainability (e.g., Jabareen 2006; Hofstad 2012; Joss 2011; Girardet 2008; Williams et al. 2000). Unquestionably, it has inspired and motivated a generation of urban scholars and practitioners into a quest for the immense opportunities created by the development of sustainable urban forms—i.e., the contribution that such forms can make as to lowering energy use and lessening pollution and waste levels, while improving human life quality and well-being. Therefore, the idea of applying the concept of sustainable development to urban form has intensively been investigated and discussed by researchers and planners during the last decade (see Kärrholm 2011). In Achieving Sustainable Urban Form, Williams et al. conclude that sustainable urban forms are "characterized by compactness (in various forms), mix of uses, and interconnected street layouts, supported by strong public transport networks, environmental controls and high standards of urban management" (Williams et al. 2000, p. 355). It is useful to operationalize the term "urban form" for the purpose of its application in this context. According to Lynch (1981, p. 47), urban form is "the spatial pattern of the large, inert, permanent physical objects in a city." In more detail, urban form as aggregations of repetitive elements denotes amalgamated characteristics pertaining to land-use patterns, spatial organizations, and other urban design features, as well as transportation systems and environmental and urban management systems (Handy 1996; Williams et al. 2000). Subsequently, urban form results from bringing together many urban patterns, which "are made up largely of a limited number of relatively undifferentiated types of elements that repeat and combine" (Jabareen 2006, p. 39). Therefore, these patterns entail similarities and grouped conceptual categories (Lozano 1990) that encompass such elements as building densities, street patterns, block sizes and shapes, spatial scales, area configurations, street designs, park layouts, and public space arrangements (Jabareen 2006; Van Assche et al. 2013). As instances of sustainable cities, sustainable urban forms denote human settlements that seek to meet the required level of sustainability by enabling urban systems and domains to function in a constructive and efficient way and to be planned in a strategic manner—with the aim of primarily improving their contribution to the goals of sustainable development.

Using a thematic analysis approach, Jabareen (2006) classifies sustainable urban forms into four models entailing overlaps among them in their concepts, ideas, and visions: (1) compact city, (2) eco-city, (3) neotraditional development (new urbanism), and (4) urban containment. This chapter is concerned with the first three urban forms in terms of integrating the underlying typologies and design concepts with the core enabling technologies and their novel applications pertaining to ICT of the new wave of computing (particularly in terms of big data analytics and context-aware computing). The rationale for focusing on these three urban forms lies in the fact that they have been ranked as the most sustainable, with the compact city being the first, the eco-city the second, and the neotraditional development (new urbanism) the third, according to Jabareen (2006). Compact city emphasizes density, compactness, and mixed-land use; eco-city focuses on ecological and cultural diversity, passive solar design, renewable resources, urban greening, environmental management, and environmentally sound policies; and new urbanism emphasizes sustainable transportation, mixed-land use, diversity, compactness, greening, and design coding (Jabareen 2006). The effects of models of sustainable urban form are compatible with the goals of sustainable development. They involve transport provision, travel behavior, mobility, accessibility, energy efficiency, pollution reduction, economic viability, life quality, and social equity.

Compact City

The compact city was first proposed by Dantzing and Saaty (1973), whose vision was to enhance the quality of life but not at the expense of the next generation—an idea that is in line with the principles of sustainable development. The notion and development of compact city were revived by the popularization of sustainable development, and hence became a preferred response to the challenge of sustainability since the early 1990s (e.g., Jenks and Dempsey 2005). Sustainable development provides the basis for the argument for the compact city (Welbank 1996). The notion of compact city entails "many strategies that aim to create compactness and density that can avoid all the problems of modernist design and cities. The popularization of sustainable development has contributed to the promotion of the urban compactness idea by enhancing the ecological and environmental justifications behind it" (Jabareen 2006, p. 46). As to combining compactness and mixed-land use, it was around the mid-1990s when research generally led to its advocacy (Jabareen 2006). For a sustainable urban form, mixed-land use should be encouraged in cities (Breheny 1992). Essentially, the compact city is a high-density, mixed-use city, and without sprawl (Jenks et al. 1996a; Williams et al. 2000). It ideally secures socially beneficial, economically viable, and environmentally sound development through dense, diverse, and mixed-use patterns that rely on sustainable transportation (Burton 2000, 2002; Dempsey 2010; Dempsey and Jenks 2010; Jenks and Dempsey 2005). The Commission of European Communities (1990) advocates very strongly the compact city, as it enhances the quality of life and makes urban areas more environmentally sustainable. In particular, the compact city is more energy efficient and less polluting because its dwellers can live closer to shops and work and can walk, bike, or take transit. Therefore, it offers the opportunity to reduce fuel consumption for traveling because work and leisure facilities are in close proximity, reuse urban land, and support local facilities, in addition to protecting rural land from further development (Jabareen 2006). Heterogeneous zoning enables compatible land uses to locate in close proximity to one another and hence shorten the travel distances between activities (Parker 1994), in addition to reducing the use of automobiles for commuting, shopping, and leisure trips due to nearby location (Alberti 2000; Van and Senior 2000). In other words, with many services and facilities being within a reasonable distance, people are encouraged to cycle and walk. Newman (2000) found that the compact city is the

Table 2.1 Compact city characteristics

1. High residential and employment densities
2. Mixture of land uses
3. Fine grain of land uses (proximity of varied uses and small relative size of land parcels)
4. Increased social and economic interactions
5. Contiguous development (some parcels/structures may be vacant or abandoned or surface parking)
6. Contained urban development, demarcated by legible limits
7. Urban infrastructure, especially sewerage and water mains
8. Multimodal transportation
9. High degrees of accessibility: local/regional
10. High degrees of street connectivity (internal/external), including sidewalks and bicycle lanes
11. High degree of impervious surface coverage
12. Low open—space ratio
13. Unitary control of planning of land development, or closely coordinated control
14. Sufficient government fiscal capacity to finance urban facilities and infrastructure

Source Neuman (2005)

most fuel-efficient of sustainable urban forms, and concluded that urban form does matter beyond the urban air quality. In all, integrating land use, transport, and environmental planning is important to minimize the need for travel and hence to promote efficient modes of transport (Sev 2009). In addition, population densities are adequate as to supporting local services and businesses (Williams et al. 2000). The compact city can, like other sustainable urban forms, be implemented across various scales, including creating entirely new settlements. To sum up, the model of compact city has been advocated for the following reasons: “First, compact cities are argued to be efficient for more sustainable modes of transport. Second, compact cities are seen as a sustainable use of land. By reducing sprawl, land in the countryside is preserved and land in towns can be recycled for development. Third, in social terms, compactness and mixed uses are associated with diversity, social cohesion, and cultural development. Some also argue that it is an equitable form because it offers good accessibility. Fourth, compact cities are argued to be economically viable because infrastructure, such as roads and street lighting, can be provided cost—effectively per capita.” Neuman (2005) summarizes the characteristics of compact city, illustrated in Table 2.1.

New Urbanism

The neotraditional planning is one of the models of sustainable urban form that has resulted from the endeavor of many scholars, planners, and architects motivated by sustainable development to seek forms for human settlement and living that will meet the required level of sustainability and enable the built environment to function in a constructive way. This sustainable urban planning strategy emphasizes physical design qualities and involves several approaches (e.g., new urbanism, urban village, and transit-oriented development). Of these, the new urbanism approach is the best known. It seeks to arrest inner-city decline suburban sprawl and to develop and redevelop neighborhoods, districts, and cities, thereby advocating design-based strategies based on traditional urban forms or drawing on historical precedents for ways of having neighborhoods based on blending different combinations of housing types (Bohl 2000; Jabareen 2006). New urbanists believe that the residential design features (e.g., narrower streets, street trees, front porches, shallow setbacks, and public open space) of new urbanism strengthen a sense of community, satisfy residents, promote local walking and use, and encourage pleasing neighborhood contacts, while increasing residential densities beyond the suburban norm (Leccese and McCormick 2000). Accordingly, new urbanism shares density as a key typology of compact city in terms of residential design, in addition to promoting diversity by mixing housing types based on incomes and household structures, thus reinforcing human presence and interaction by taming the ubiquitous automobile and providing for human contact in the neighborhood (Audirac and Shermyen 1994; Leccese and McCormick 2000). It emphasizes other concepts of sustainable urban form, including pedestrian orientation and walkable villages as to transport and a mix of residential, commercial, and civic uses as to mixed-land use.

However, some scholars argue that there is a gap between the discourse of new urbanism and its practice in real-life settings. In more detail, while designs features of new urbanism are claimed to entail higher density, more compactness, and more walking (due to mixed-land use) than suburban places (Beasley 2000), their reality does not go hand in hand with their rhetorical aspirations, and particularly their densities often lack some ingredients (mixed-land use, public transport, etc.) that could make them more sustainable (Jabareen 2006; Kreiger 1998). In this line of thinking, Kreiger (1998) contends that new urbanism projects provide a new legitimation of low-density, peripherally located, home-dominated real estate development, in addition to subdivisions and homogeneous demographic enclaves. Also, Beatley (2000) criticizes such projects for rarely promoting more ecologically sustainable lifestyles or being concerned with reducing ecological impacts. Therefore, "what we need today are cities that reflect a different new urbanism, a new urbanism that is dramatically more ecological in design and functioning and that has ecological limits at its core" (Beatley 2000, p. 5). Furthermore, new urbanism "is by necessity a fully planned and regulated environment, fiercely resistant to change and any deviation from the rigid rules that govern its form and function. But it is precisely this inflexibility, which is so important in its struggle for completion as a development enterprise" (Durack 2001, p. 64). This argument sides with Neuman's (2005) view regarding the static conception of urban forms and its disadvantages. Indeed, Durack (2001) argues for open, indeterminate planning due to its advantages, namely, cultural diversity; tolerance and value of topographic, social, and economic discontinuities; citizen participation; and continuous adaptation, which is common to human settlements like all other living organisms and systems.

Eco-city (and Green Urbanism)

The concept of eco-city is widely varied and difficult to delineate. Joss (2010), who carried the most comprehensive survey of eco-cities to date in 2009–2010, acknowledges that the conceptual diversity and plurality of projects and initiatives using the term makes it difficult to develop a meaningful definition. Therefore, eco-city has taken on many definitions in the literature. Richard Register, an architect widely credited as the first to have coined the term defined eco-city as "an urban environmental system in which input (of resources) and output (of waste) are minimized" (Register 2002). Opting for defining the term using three analytical categories, Joss (2011) states that an eco-city must be developed on substantial scale, occurring across multiple domains, and supported by policy processes. Rapoport and Vernay (2011, p. 2) conceive of eco-city "as a way of practically applying existing knowledge about what makes a city sustainable to the planning and design of new and existing cities." According to Jabareen (2006, p. 47), eco-city as an umbrella metaphor "encompasses a wide range of urban-ecological proposals that aim to achieve urban sustainability. These approaches propose a wide range of environmental, social, and institutional policies that are directed to managing urban spaces to achieve sustainability. This type promotes the ecological agenda and emphasizes environmental management through a set of institutional and policy tools." This implies that realizing an eco-city requires making numerous decisions about urban form as to design concepts, building design, sustainable technologies, and governance (Rapoport and Vernay 2011). In view of that, the link between the goals of sustainable development and the urban design and planning interventions is a subject of much debate (Bulkeley and Betsill 2005; Williams 2009).

Several sets of criteria have been proposed to identify what an "eco-city" is, entailing economic, social, and environmental goals of sustainability. According to Roseland (1997) and Harvey (2011), the ideal "eco-city" is a city that fulfills the following set of requirements: operates on a self-contained, local economy; maximizes efficiency of energy resources; is based on renewable energy production and carbon neutrality; has a well-designed urban city layout and sustainable transport system (prioritizing walking, cycling, and public transportation); creates a zero-waste system; support urban and local farming; ensures affordable housing for diverse socioeconomic and ethnic classes; raises awareness of environmental and sustainability issues, decreases material consumption; and, added by Graedel (2011), is scalable and evolvable in design in response to population growth and need changes. Based on these characteristic features, it is noticeable that eco-city and green urbanism share several ideas and visions in terms of the role of the city and positive urbanism in shaping more sustainable places, communities, and lifestyles. Arguing for the need for new approaches to urbanism to incorporate more ecologically responsible forms of living and settlement, Beatley (2000, pp. 6–8, cited in Jabareen 2006) views a city exemplifying green urbanism as one that "(1) strives to live within its ecological limits, (2) is designed to function in ways analogous to nature, (3) strives to achieve a circular rather than a linear metabolism,

(4) strives toward local and regional self-sufficiency, (5) facilitates more sustainable lifestyles, and (6) emphasizes a high quality of neighborhood and community life." The eco-city approaches tend to emphasize different aspects of sustainability, namely, passive solar design, sustainable housing, greening and passive energy design, sustainable urban living, and living machines (Jabareen 2006). Important to note is that the eco-city is conceived as formless or ecoamorphous as to some typologies such as density, although it emphasizes passive solar and ecological design (Jabareen 2006). Indeed, it is evident that a specific urban form is of less focus in the eco-city, that is, the built environment of the city is unimportant, unlike the compact city and new urbanism which focus on the physical and design features; rather, what counts most is how the city as a social fabric is organized and managed. As supported by Talen and Ellis (2002, p. 37) in this regard, "social, economic, and cultural variables are far more important in determining the good city than any choice of spatial arrangements." Hence, the focus is on the role of different environmental, social, economic, institutional, and land-use policies in managing the city to achieve sustainability (e.g., Council of Europe 1993; European Commission 2012; Jabareen 2006; Robinson and Tinker 1998).

2.2.1.4 Smart Sustainable Cities

The concept of smart sustainable cities is gaining increasing attention worldwide, from research institutes, universities, governments, policymakers, and ICT companies, as a response to the imminent challenges of sustainability and urbanization. It became widespread during the mid-2010s (e.g., Al-Nasrawi et al. 2015; Angelidou et al. 2017; Bibri and Krogstie 2016a, 2017a, b, c; Höjer and Wangel 2015; Kramers et al. 2014, 2016) as a result of several intertwined global shifts at play across the world, namely, the diffusion of sustainability, the spread of urbanization, and the rise of ICT. As echoed by Höjer and Wangel (2015), the interlinked development of sustainability, urbanization, and ICT has recently converged under what is labeled "smart sustainable cities." The basic idea is to leverage the potential and ubiquity of advanced ICT in the transition toward the needed sustainable development in an increasingly computerized and urbanized world.

The term "smart sustainable city," although not always explicitly discussed, is used to describe a city that is supported by the pervasive presence and massive use of advanced ICT, which, in connection with various urban systems and domains and how these intricately interrelate and are coordinated, respectively, enables the city to control available resources safely, sustainably, and efficiently to improve economic and societal outcomes. The combination of smart cities and sustainable cities, of which many definitions are available, has been less explored as well as conceptually difficult to delineate due to the multiplicity and diversity of the existing definitions (see Bibri and Krogstie 2017a for an overview). ITU (2014) provides a comprehensive definition based on analyzing around 120 definitions, "a smart sustainable city is an innovative city that uses…ICTs and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental aspects." Another definition put forth by Höjer and Wangel (2015, p. 10), which is deductively crafted and based on the concept of sustainable development, states that "a smart sustainable city is a city that meets the needs of its present inhabitants without compromising the ability for other people or future generations to meet their needs, and thus, does not exceed local or planetary environmental limitations, and where this is supported by ICT." This entails unlocking and exploiting the potential of ICT of pervasive computing as an enabling, integrative, and constitutive technology for achieving the environmental, social, and economic goals of sustainability due to the underlying transformational, substantive, and disruptive effects. Another conceptualization of the term provided by Bibri and Krogstie (2016a, p. 11) states: "as a dynamic, complex interplay between scientific innovation, technological innovation, environmental innovation, urban design and planning innovation, institutional innovation, and policy innovation, smart sustainable cities represent and involve inherently complex socio-technical systems of all sorts of innovation systems. Such systems, which focus on the creation, diffusion, and utilization of knowledge and technology, are of various types (variants of innovation models), including national, regional, sectoral, technological, and Triple Helix of university-industry-government relations."

As ICT permeates infrastructures, architectural and urban designs, ecosystem services, human services, and citizens' objects, we can speak of cities getting smarter as to addressing environmental, social, and economic problems, as well as providing services to citizens to improve the quality of their life (Batty et al. 2012; Bibri and Krogstie 2016a, 2017a; Piro et al. 2014; Shepard 2011; Townsend 2013). Indeed, this pervasion of ICT into urban environments implies new and more extensive sources of urban data, which can provide immense possibilities to better monitor, understand, analyze, and plan smart sustainable cities to improve their contribution to the goals of sustainable development. The increasing convergence of ICT of various forms of pervasive computing is increasingly seen as a way to capture further and invigorate the application demand for the many solutions for urban sustainability that emerging and future ICT can offer. The ability of computerizing urban systems and domains and hence thinking data-analytically and based on context information about how to enhance their contribution to the different dimensions of sustainability constitutes an indication of the reach of the gravitational field of ICT of pervasive computing's effort to develop innovative solutions and sophisticated approaches from the ground up for smart sustainable cities of the future. Therefore, the potential of monitoring, understanding, analyzing, and planning cities through advanced ICT can well be leveraged in advancing sustainability. Indeed, smart cities (e.g., Al Nuaimi et al. 2015; Batty et al. 2012) and sustainable cities (e.g., Bibri and Krogstie 2017b; Kramers et al. 2014; Shahrokni et al. 2015) that are engaging on the new transition in ICT are getting smarter in achieving the required level of sustainability. As complex systems par excellence, smart sustainable cities rely more and more on sophisticated technologies and their novel applications to realize their full potential and thus respond to the challenge of sustainability. The most prevalent of these technologies and their applications, which are prerequisite for realizing ICT of pervasive computing, are UbiComp, AmI, the IoT, and SenComp and related big data analytics and context-aware computing in relation to sustainable urban development (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a; Böhlen and Frei 2009; Kyriazis et al. 2014; Shepard 2011; Solanas et al. 2014). Big data analytics and context-aware computing as rapidly growing areas of ICT are becoming of crucial importance to the operational functioning and planning of smart sustainable cities (Bibri and Krogstie 2016b). Therefore, the expansion of these computing waves is increasingly stimulating the development of different models of smart sustainable city as urban initiatives and projects.

2.2.1.5 The Built Environment

The built environment has been referred to by a variety of terms which seem interchangeable. It is described by Handy et al. (2002) as consisting of land use, urban design, and the transportation system, and encompassing patterns of human activity and mobility within the physical environment. Past urban studies have typically focused on different spatial levels of the built environment, especially the neighborhood level and the regional scale. Handy et al. (2002) discuss measures of the built environment by categorizing them into neighborhood and regional features, with at least five interrelated and often correlated dimensions of the built environment at the neighborhood scale, as suggested by several studies (Table 2.2).

The existing built environment, ranging in scale from neighborhoods to cities and regions, is associated with numerous environmental, social, and economic impacts, including unsustainable energy use and concomitant GHG emissions, increased air and water pollution, environmental degradation, land-use haphazard, inappropriate urban design and related social deprivation and community disruption, ineffective mobility and accessibility, increased transport needs and traffic congestion, public safety and health decrease, but to name a few. The built form of the contemporary city affects people, natural resources, habitat, and climate (e.g., Jabareen 2006). These effects are expected to worsen with the increasing urbanization of the world. Urban growth raises a variety of problems that jeopardize the environmental, economic, and social sustainability of cities (e.g., Neirotti et al. 2014), as well as render the conception of cities in terms of forms inadequate to achieve the goals ascribed to sustainable urban forms (Neuman 2005). Specifically, urban growth engenders such issues as intensive energy consumption, endemic congestion, saturated transport networks, air and water pollution, toxic waste disposal, resource depletion, environmental degradation, inadequate decision-making and planning systems, inefficient management of urban infrastructures and facilities, poor housing and working conditions, social inequality and vulnerability, public health decrease, and so on. In a nutshell, as a dynamic clustering of people, buildings, infrastructures, and resources, urbanization puts an enormous strain on

Table 2.2 Dimensions of the built environment

Dimension	Definition	Examples
Density and intensity	Amount of activity in a given area	Persons per acre or jobs per square mile Ratio of commercial floor space to land area
Land-use mix	Proximity of different land uses	Distance from house to nearest store Share of total land area for different uses Dissimilarity index
Street connectivity	Directness and availability of alternative routes through the network	Intersections per square mile of area Ratio of straight-line distance of network distance Average block length
Street scale	Three-dimensional space along a street as bounded by buildings	Ratio of building heights to street width Average distance from street to buildings
Aesthetic quality	Attractiveness and appeal of a place	Percent of ground in shade at noon Number of locations with graffiti per square mile
Regional structures	Distribution of activities and transportation facilities across the region	Rate of decline in density with distance from downtown Classification based on concentrations of activity and transportation network

the built environment and the underlying systems and processes, i.e., the physical structures and urban infrastructures and the related operations, functions, and services. Sustainable urban development represents a process of change in the built environment, which promotes the health of citizens, communities, and natural ecosystems and fosters economic development while conserving resources in the face of urbanization. The way forward for cities to better cope with the restructuring and changing conditions is to adopt the long-term approach that emphasizes sustainability (see Bulkeley and Betsill 2005).

2.2.1.6 Typologies and Design Concepts of Models of Sustainable Urban Form

To achieve sustainable urban forms requires such typologies as compactness, density, diversity, and mixed-land use, and such design concepts as sustainable transport, ecological design, and passive solar design, supported by high standards of environmental and urban management (Dumreicher et al. 2000; Jabareen 2006; Williams et al. 2000). Next, we describe and discuss the most prevalent typologies and design concepts of sustainable urban forms.

Compactness

The notion of compactness of the built environment or urban space as a widely acceptable strategy for achieving more sustainable urban forms entails that future urban development should be driven by contiguity and connectivity in the sense of taking place adjacent to existing urban structures (Jabareen 2006; Wheeler 2002). Compactness emphasizes "density of the built environment and intensification of its activities, efficient land planning, diverse and mixed-land uses, and efficient transportation systems" (Jabareen 2006, p. 46). At the core of compactness is the intensification of the built form, which involves using land use more efficiently by increasing the densification in terms of development and activities. This intensification includes mainly development of not fully or less developed urban land and redevelopment of previously developed sites, as well as additions and extensions and conversions and subdivisions (Jenks 2000). Indeed, the concept of compactness also refers to the containment of further sprawl when the concept is applied to existing rather than new urban fabric (Hagan 2000). As major themes evident in current debates on compactness as a strategy for achieving desirable urban forms, the positive effects of sustainability include promoting the quality of life in terms of social interaction and accessibility to facilities and services, providing building densities for energy conservation, and minimizing the number and length of trips by modes of transport (involving energy, materials, water, products, and people) detrimental to the environment in terms of CO_2 emissions, and protecting rural land (e.g., Elkin et al. 1991; McLaren 1992; Pratt and Larkham 1996; Williams et al. 2000).

Density

As a critical typology of sustainable urban forms, density denotes the ratio of dwelling units or buildings and their inhabitants to land area. The densities and scaling relations of cities allow for green urban planning, low-carbon urban mobility, high resource efficiency of buildings (EEA 2015). To make urban functions or activities viable depends on the sufficiency of generating the necessary interactions, which is based on the number of people within a given area (Jabareen 2006). In fact, sustainable cities are about density (Carl 2000) and dwelling type, which affect sustainability through differences in the consumption of resources as well as land for housing and urban infrastructure (Walker and Rees 1997). As major themes evident in current debates on density as a strategy for achieving desirable urban forms, the claimed sustainability benefits involve saving energy by slashing its consumption, achieving urban efficiency, minimizing automobile travel needs and thus emissions, and providing accessibly to facilities (e.g., Jabareen 2006; Newman and Kenworthy 1989; Walker and Rees 1997). Density relates to compactness in that high density and integrated land use, in addition to conserving resources, provide for compactness that encourages social interaction (Jabareen 2006).

Mixed-Land Use

Commonly, land use refers to the distribution of activities across space, grouped into relatively coarse categories. Widely recognized among scholars and planners for its important role in achieving sustainable urban form, mixed-land use (heterogeneous zoning) signifies the diversity and proximity of land uses in terms of functioning, such as institutional, infrastructural, cultural, residential, commercial, and industrial. This is to mainly decrease the travel needs and distances between activities or functions due to the availability and proximity of many services and facilities. As major themes evident in current debates on mixed-land use as a strategy for achieving desirable urban forms, the positive effects of sustainability include enhancing accessibility to services and facilities; reducing automobile use for various purposes; decreasing the travel distances between activities, encouraging cycling or walking, improving security in public spaces for disadvantaged groups; reducing air pollution and traffic congestion, and stimulating the interaction of residents by increasing pedestrian traffic, and decreasing vehicle trip generation rates and traveled time (e.g., Alberti 2000; Elkin et al. 1991; Ewing 1995; Jabareen 2006; Newman 1997; Parker 1994; Thorne and Filmer-Sankey 2003; Van and Senior 2000).

Diversity

Diversity is widely adopted by several planning approaches, such as new urbanism, sustainable urbanism, and smart growth. Diversity of functions and typologies is essential to modern cities and their sustainability. Without diversity, the urban system declines as a living place (see Jacobs 1961). Diversity has been a pervasive and persistent feature of sustainability debates and a powerful idea of redefining such debates (Taylor 1986; Neuman 2005). Overlapping with mixed-land uses in urban planning, diversity entails, in addition to a mixture and multiplicity of land uses, building densities, a variety of housing types, housing for all income groups through inclusionary zoning, job-housing balances, household sizes and structures, cultural diversity, and age groups (e.g., Jabareen 2006; Wheeler 2002), thereby epitomizing the sociocultural context of the urban form. Topographic and functional diversity is requisite for social and cultural mixture and integration (Peterek 2012). As major themes evident in current debates on diversity as a strategy for achieving desirable urban forms, the corollaries of sustainability are varied. Diversity reduces traffic congestion and air pollution (Wheeler 2002). In "diversified city areas, people still walk, an activity that is impractical in the suburbs and in most gray areas. The more intensely various and close-grained the diversity in an area, the more walking. Even people who come into a lively, diverse area from outside, whether by car or by public transportation, walk when they get there" (Jacobs 1961, p. 230). To note, the developments around the public transit node are supposed to promote diversity as a multidimensional phenomenon in terms of greater variety of housing types, building densities, household sizes, cultures, and incomes. An urban development without such features leads to “increased driving, congestion, and air pollution” (Wheeler 2002, p. 328). Wheeler (2002) argues that diverse building types and land uses are today important to vibrant, attractive, and popular neighborhoods and districts, and concludes that zoning has diminished the diversity of urban form. For a sustainable urban form, zoning should be discouraged (see Breheny 1992).

Sustainable Transport

The transportation system entails both the physical infrastructure, including roads, railroad tracks, sidewalks, and bike paths, as well as the level and quality of service provided as determined by traffic levels and train and bus frequencies. It has been argued that transport is the major issue for environmental debates relating to urban form (Jenks et al. 1996a). Sustainable transportation is described by Jordan and Horan (1997, p. 72) as “transportation services that reflect the full social and environmental costs of their provision; that respect carrying capacity; and that balance the needs for mobility and safety with the needs for access, environmental quality, and neighborhood livability.” Diminishing mobility and negative traffic are at the core of sustainability (Clercq and Bertolini 2003). Elkin et al. (1991) contend that sustainable urban form must be appropriate to efficient public transport, walking, and cycling. Among the major themes evident in current debates on sustainable transportation as a strategy for achieving sustainable urban forms, include operating transport at maximum efficiency, providing favorable conditions for energy-efficient forms of transport, reducing the need for mobility, providing equitable accessibility to services and facilities, limiting CO_2 emissions and waste, promoting renewable energy sources, decreasing travel needs and costs, minimizing land use, achieving a healthy and desirable quality of life in each generation, supporting a vibrant economy, and conserving energy in several ways (e.g., Cervero 1998, 2003; Duncan and Hartman 1996; Elkin et al. 1991; Jabareen 2006; Jordan and Horan 1997). Therefore, sustainable urban development policies should consider measures to provide favorable conditions for energy-efficient and environmentally friendly forms of transport as well as to reduce the need for movement as objectives that can be attained through land-use planning (Jabareen 2006).

Greening—Ecological Design

Green urbanism or infrastructure is an important design concept in sustainable urban planning. Green space has the ability to contribute positively to sustainability agenda (Swanwick et al. 2003). In addition to making urban places attractive and pleasant (Nassauer 1997; Van der Ryn and Cowan 1995), greening urban spaces renders them more sustainable (Dumreicher et al. 2000) by bringing nature into the life of citizens through diverse open landscapes (Elkin et al. 1991). In addition to these contributions, there are key themes evident in current debates on greening urban spaces as a strategy for achieving desirable urban forms. These themes pertain to sustainability benefits, including moderating urban climate extremes, preserving and enhancing the ecological diversity of the environment of urban places, maintaining biodiversity through the conservation and enhancement of the distinctive range of urban habitats, improving the urban image and the quality of life, enhancing health benefits, ameliorating the physical urban environment by reducing pollution, and increasing economic attractiveness in urban areas (e.g., Beer et al. 2003; Gilbert 1991; Jabareen 2006; Niemela 1999; Von Stulpnagel et al. 1990; Ulrich 1999; Plummer and Shewan 1992). Thus, it is crucially important for new approaches to urbanism to incorporate more ecologically responsible forms of settlement and living (Beatley 2000).

Passive Solar Design

Passive solar design is one of the key design concepts and principles for achieving a sustainable urban form. It entails reducing the demand for energy and the sustainable use of passive energy through particular design measures (Jabareen 2006). Passive cooling and heating through orientation is a useful method to maximize the use of renewable resources from the site such as solar energy (Karolides 2002). The greater environmental impacts and contextual implications of the building in relation to the site are two criteria to look at by the designer, adding to searching for different alternatives to orient the building according to the sun path for passive solar gain and daylighting (Gordon 2005; Yeang 1997). Passive solar design techniques can be applied to both new buildings as well as existing buildings through retrofitting. By means of design, orientation, layout, and landscaping solar gain and microclimatic conditions can be used in an optimal way to minimize the need for buildings' space heating or cooling by conventional energy sources (Owens 1992). The orientation of buildings and urban densities as a design feature affects the form of the built environment (Thomas 2003). The built form, coupled with the street widths and orientation, largely determine urban surfaces' exposure to the sun (Jabareen 2006). The energy systems and urban structures interact at all spatial scales, ranging from the regional, city, community, and neighborhood to the building (Owens 1992). Orientation and clustering of buildings determined by the settlement formation of a city affects the microclimatic conditions (Jabareen 2006). Yannas (1998, cited in Jabareen 2006, p. 42) summarizes some design parameters for achieving environmentally sustainable urban forms and improving urban microclimate: "(1) built form—density and type, to influence airflow, view of sun and sky, and exposed surface area; (2) street canyon—width—to—height ratio and orientation, to influence warming and cooling processes, thermal and visual comfort conditions, and pollution dispersal; (3) building design—to influence building heat gains and losses, albedo and thermal capacity of external surfaces, and use of transitional spaces; (4) urban materials and surfaces finish—to influence absorption, heat storage, and emissivity; (5) vegetation and bodies of water—to influence evaporative cooling processes on building surfaces and/or in open spaces; and

(6) traffic—reduction, diversion, and rerouting to reduce air and noise pollution and heat discharge." In all sustainable urban design has a tremendous potential in reducing the environmental impacts of the built environment, e.g., reduction of energy usage, and it is associated with several other benefits.

2.2.1.7 Urban ICT

The theoretical and disciplinary orientation of computing and ICT differentiate their meaning, despite their close relation. Hence, it is worth pointing out the main difference to give perspective. ICT theory is concerned with the application of technology in, and its effects on, society, and computing theory deals with the way ICT systems are designed, developed, and implemented as well as how they function (Bibri 2015b).

Information and communication technology (ICT) theory has been applied to almost all human endeavors and thus spheres of society. In the sphere of urban planning and development, the concept of ICT refers to a set of urban infrastructures, architectures, applications, systems, and computational and data analytics capabilities—i.e., constellations of hardware and software instruments across several scales connected through wirelessly ad hoc and mobile networks which provide continuous data regarding the physical, spatiotemporal, infrastructural, operational, functional, and socioeconomic forms of the city. These technological components are employed for sensing, collecting, storing, coordinating, integrating, processing, analyzing, synthesizing, manipulating, modeling, simulating, managing, exchanging, and sharing urban data for the purpose of monitoring, understanding, probing, and planning modern cities to achieve particular goals. To put it differently, the aim of applying ICT to urban domains and systems and thus using the underlying core enabling technologies and data-centric applications is to better comprehend how cities function and can be managed as complex systems to derive new theories, devise new solutions, formalize and implement new methods, and study and evaluate processes. This entails a variety of ways of remedying a wide range of problems affecting the long-term health and efficiency of the city as well as the quality of life of its citizens.

At the technical level, urban ICT includes hardware and software components. The former encompass sensors (RFID, GPS, infrared sensors, smart sensors, wearable devices, etc.), computers and terminals, smartphones, Internet infrastructure, wireless communication networks, telecommunication systems, database systems, cloud computing infrastructure, and middleware architecture. The latter includes all kind of software applications operating and running on these hardware systems, including big data analytics techniques (data mining, machine learning, statistical analysis, and natural language processing, etc.), database integration and management methods, modeling and simulation methods, visualization methods, real-time operation methods, enterprise integration methods, decision support systems, and communication and networking protocols. ICT spans over scores of urban domains and sub-domains and hence can be integrated into built form, infrastructure, architecture, networks, facilities, services, spatial organizations, and physical objects, as well as attached to citizens and spread along the trajectories they follow during their daily activities. Urban ICT can be best spoken of based on the context of use, e.g., smart transport, smart mobility, smart traffic, smart energy, smart planning, smart governance, smart environment, smart health care, smart education, smart safety, and smart parks.

2.2.1.8 Urban Computing

Urban computing has been used interchangeably with urban ICT, despite the distinction between the two concepts. Computing can mean a process or a field. As a process, it entails the use of computer technology to complete a task, i.e., process data or perform calculations. As such, it may involve computer hardware and/or software, but must involve some form of a computer system. As a process of heterogeneous data collection, integration, processing, analysis, and synthesis (Zheng et al. 2014), urban computing is a set of computational tools, techniques, methods, and systems (e.g., big data analytics, context-aware computing) to tackle the issues engendered by the rapid urbanization and the challenge of sustainability facing cities by using, manipulating, and leveraging various kinds of urban data, e.g., human mobility data, spatiotemporal data, traffic flow data, environmental data, energy data, transport data, and socioeconomic data, to enhance decision-making and planning processes.

As an interdisciplinary field, urban computing consists of a range of scientific and technological areas (e.g., computer science, information science, information technology, information systems, computer and software engineering, and wireless and sensor networks) and city-related or urban planning fields (e.g., environmental planning, transportation planning, land-use planning, landscape architecture, civil engineering, urban design, ecology, and economy) converge in the context of urban spaces. Accordingly, urban computing deals with the study, design, development, and implementation of computing technology in urban systems and domains. Specifically, it is concerned with designing and constructing urban-oriented systems and applications and making them behave intelligently as to decision support to serve multiple urban goals; representing, modeling, processing, and managing various kinds of urban data; collecting information and discovering knowledge for various purposes; and so forth. Urban computing employs many of the technological paradigms introduced by the new wave of computing, i.e., the integration and large-scale use of various forms of pervasive computing, mainly UbiComp, AmI, the IoT, and SenComp. These represent an era when, in the urban context, computer technology in all its forms disappears into urban environments and recedes into the background of urban life, to draw on Weiser (1991). The new wave of computing shares the same core enabling technologies, namely, sensing devices, computing infrastructures, data processing platforms, and wireless communication networks. These are to function unobtrusively and invisibly in the background of urban life to—by means of various ICT applications—help optimize urban operational functioning, improve urban management and planning, enhance the quality of life of citizens, understand the nature of urban phenomena, and predict urban changes. The new wave of computing is associated with the amalgamation of the most prevalent visions of ICT, namely, UbiComp, AmI, the IoT, and SenComp, whose definitions, characteristics, differences, and overlaps are the object of the next section.

2.2.1.9 Context-Aware Computing

HCI Applications Versus Urban Systems

As a fundamental aspect of everyday life, context shapes, influences, and changes the patterns underlying the interaction of all kinds of intelligent entities, e.g., humans, computers, and engineered systems, with their environment. Context-aware computing has been researched extensively by the HCI community since the late 1990s (e.g., Criel and Claeys 2008; Dey 2000, 2001; Schmidt et al. 1999; Ulrich 2008). As a prerequisite for realizing the various ICT visions of pervasive computing, it aims to support human action, interaction, and communication in various ways wherever and whenever needed by enabling sensorily and computationally augmented environments to provide the most efficient services pertaining to health care, education, learning, safety, utility, housing, and so on. This occurs through relying on diverse contextual information about users in order to anticipate and respond intelligently to their needs and desires in a seamless and unobtrusive way. It is becoming increasingly evident that smart environments—especially within smarter cities as future forms of smart cities, namely, ambient cities, sentient cities, ubiquitous cities, Internet-of-everything, and real-time cities (e.g., Batty et al. 2012; Böhlen and Frei 2009; Kitchin 2014; Kyriazis et al. 2014; Lee et al. 2008; Perera et al. 2014; Shepard 2011; Shin 2009; Zanella et al. 2014)—which can support urban life through context-aware service provision and decision support, will be commonplace in the near future. This postulates that everyday urban environments are to be pervaded by powerful new forms of ICT to enable context-aware functionalities: "humans will be surrounded and accompanied by advanced sensing and computing devices, multimodal user interfaces, intelligent software agents, and wirelessly ad hoc networking technologies, which are everywhere, invisibly woven into the fabric of [urban] space, in virtually all kinds of everyday objects [computers, mobile phones, doors, walls, lights, switches, appliances, vehicles, roads, water flow, etc.] in the form of tiny microelectronic processors and networks of miniature sensors and actuators, functioning unobtrusively in the background of human life" (Bibri 2015a, p. 3). With the underlying logically malleable nature lending itself to multifarious functionalities, this seamless computing environment becomes able to, by using autonomous active devices, aid citizens in coping with their daily activities through providing them with unlimited services in new ways within a variety of settings. By the same token, as context-aware technologies aim to, in addition to providing services, control over processes and support decision-making, urban systems can use context-aware functionalities to operate and organize urban life in terms of control, management, optimization, and planning. The pervasion of advanced ICT into urban spaces in the form of a variety of networked sensor-based devices and information processing systems deployed on the wide-city scale constitute new opportunities to support urban life activities and processes. This indeed characterizes the abovementioned faces of smart cities. Such cities are said to denote urban environments loaded with ICT in its various forms: sensors, information processors, cloud computing platforms, and wireless networks, and thereby saturated with clouds of data intended to shape the operational functioning and the experience of citizens of the city.

Over the last two decades, the research within context-aware computing has focused on the cognitive, emotional, physical, social, behavioral, conversational, spatiotemporal, and computational aspects of the human context in relation to daily living and work spaces (Bibri 2015a). The focus in this study as to this stream of scholarship is on the physical, spatiotemporal, and social features of the human context. However, the concept has been expanded beyond the ambit of HCI applications to include urban (and industrial) applications, such as energy systems, transport systems, communication systems, traffic systems, power grid systems, healthcare systems, education systems, security systems, and so on (e.g., Al Nuaimi et al. 2015; Bibri and Krogstie 2017b; Böhlen and Frei 2009; ISTAG 2003, 2008, 2012; Shepard 2011; Solanas et al. 2014). Here, the focus is on the physical, environmental, spatiotemporal, socioeconomic, and cultural aspects of the urban context, depending on the application domain. Related context-aware services utilize context information to "automatically deploy services for a user or control an environment, associate context information with other information, allowing subsequent access to this based on 'contextual' search criteria…[e.g. discover all information relevant to this system or environment]; personalize modes of interaction between the user and the service; select services relevant to the user in a given environment or situation (context-aware service discovery and provisioning)" (Riva et al. 2003, p. 75). Important to underscore here is that context-aware applications are aimed at providing services or controlling over/monitoring processes, in addition to supporting decision-making needs. Accordingly, a multitude of approaches and techniques have been proposed and investigated with the main difference between the two perspectives on context-aware computing being the manner in which relevant knowledge domains are modeled, represented, reasoned about, and utilized. Indeed, the availability and use of contextual information in both HCI applications and urban systems both offer new possibilities to adapt applications and systems to the current situation, thereby the context influencing and fundamentally changing the behavior of such applications and systems. With reference to cities, for example, all types of buildings "offer one of the major sources for reduction in electricity consumption by better monitoring in real-time of the ambient environment…by using more sophisticated and efficient building energy management systems and/or by using more context-aware technologies" (ISTAG 2008, p. 6). In all, the concept of context-aware computing is associated with the operational functioning of the city and the well-being and quality of life of its citizens. Indeed, smart sustainable cities are strongly based on networked sensor-based devices that provide updated information about diverse contextual variables, including transport networks, traffic conditions, spatial behaviors, human movements, pollution levels, energy usage patterns, and so on. The widespread adoption of diverse sensors within these cities provides interactions through opportunistic and people-centric sensing (Lane et al. 2008; Manzoor et al. 2014). In this context, context-aware applications and systems can monitor what is happening in urban environments (situations, events, activities, behaviors, locations, settings, etc.), analyze, interpret, and react to them in a variety of ways—be it in relation to smart energy, smart street lights, smart traffic, smart transport, smart mobility, smart health care, smart education, or smart safety—across several spatial scales. Here, context denotes, drawing on Chen and Kotz (2000), the environmental conditions within the urban landscape that either determine applications' behavior or in which application events occur and are interesting to different classes of users, including citizens, urban administrators, urban operators, urban authorities, and urban departments. The contextual variables provided by the smart sustainable cities infrastructures are understood as a means to understand the living environment of citizens and the urban operational functioning at any time. Hence, by properly using this contextual information about diverse urban aspects, it is possible to provide diverse applications and services with active context awareness, that is, that automatically adapt to discovered or recognized context, by changing their behavior accordingly. In becoming a huge system of systems, smart sustainable cities have to provide citizens and urban actors with the sensed and processed contextual information that enables them to use the provided services on demand and to manage cities and enhance their activities, respectively (see Solanas et al. 2014). Context sensing, processing, and wireless communication infrastructures are being widely deployed in urban service environments, and the wealth of information generated by multiple sensors will be utilized to better serve the needs of different classes of users, individual and collective actors operating in the urban environment. However, the pace of deployment of context-aware projects within smart sustainable cities will depend on their financial capabilities as well as the advancement of a number of background technologies. Riva et al. (2008) provide an example account of these technologies.

Context Awareness and Intelligence in the Urban Domain

As a form of computation (or analytics) performed to generate inferences from context data for decision-making purposes, context awareness is a central issue to ICT of the new wave of computing—albeit used at varying degrees in the ambit of UbiComp, AmI, the IoT, and SenComp—in the sense that it is given a prominent role in the notion of intelligence. In the urban context, the notion of intelligence alluded to with regard to ICT of various forms of pervasive computing entails that the urban environment is able to recognize situations, events, states, settings, and behaviors as contextual features pertaining to various urban domains and intelligently react to them by anticipating and responding to the citizens and systems of the city in terms of services and operations, respectively. This relates to exploring the idea of smart sustainable cities as techno-urban innovation labs, which entails developing intelligence functions as new notions of the way these cities operate. Urban intelligence functions can, by utilizing the complexity sciences in developing advanced simulation models and optimization methods, allow for monitoring and designing these cities with respect to the efficiency of energy systems, the improvement of transport and communication systems, the effectiveness of distribution networks, and the efficiency of ecosystem and public service delivery (Batty et al. 2012; Bibri and Krogstie 2017a). This has been made possible by building and maintaining models of real-time cities in terms of their operations, services, and designs on the basis of sensor-based/machine-generated data. However, the notion of urban intelligence is predicated on the assumption that complex artificial intelligence techniques are able to identify, understand, infer, and model situations of urban life in a manner that would allow the systems and applications across diverse urban domains to adaptively or proactively take the most relevant actions.

Context awareness has been defined in multiple ways, depending on the application domain in terms of the number and nature of the subsets of the context of a given entity (traffic system, energy system, healthcare system, education system, information system, human actor, etc.) that can be integrated (sensed, conceptualized, and modeled) in the design and development of a given computational artifact. Originated in pervasive computing the term “context awareness” is used to describe technology that “is able to sense, recognize, and react to contextual variables, that is, to determine the actual context of its use and adapt its functionality [and behavior] accordingly or respond appropriately to features of that context” (Bibri 2015a, p. 76). This adaptation is based either on real-time reasoning capabilities or pre-programmed heuristics. Another definition of context proposed by Dey (2000) states: “Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves.” Context-aware environments intelligently monitor different kinds of objects in the real world and interact adaptively and proactively with them, a process which occurs in an autonomous and responsible fashion, as well as in a user-authorized way, when needed. In this context, objects can be of a digital or physical nature, which can provide services to other components or control over processes. Such objects may include smartphones and other mobile devices carried by users, devices and systems installed or operating in the urban environment, and other kinds of physical objects augmented with embedded sensing, processing, and communication capabilities. Further, in more detail as to monitoring and interacting with objects, as a sensor-based perception, context awareness refers to an application-specific trait that indicates that computational artifacts (e.g., HCI applications and urban systems) are able to acquire information about the different aspects of the relevant context (physical, environmental, spatiotemporal, socioeconomic, behavioral, etc.); process, analyze, and interpret this information to generate high-level abstractions of context using machine learning, data mining, or one of the existing hybrid representation and reasoning approaches; and use such abstractions as inferences to support intelligent decision-making and action-taking processes. Accordingly, context-aware applications and systems in the realm of smart sustainable cities entail the acquisition of contextual urban data using sensors of many types to perceive situations of urban life, the abstraction of contextual urban data by matching sensory readings to specific urban context concepts, and application behavior through firing actions based on the outcome of reasoning against contextual urban information, i.e., the inferred context, to draw on Schmidt (2003). In more specific terms, the process of recognizing relevant urban contexts consists of determining the "conditions" of diverse intelligent entities pertaining to such domains as transport, traffic, energy, environment, health care, and education, including features of the way in which the relevant components of these domains interrelate according to "the universe of discourse (UoD)" (Sølvberg and Kung 1993) underlying the conceptual modeling of smart sustainable cities. And the aim is to make predictions or educated guesses about the contextual data associated with various aspects of urban operations and citizens' behaviors based on real-time reasoning or pre-programmed heuristics capabilities and then undertake actions in a knowledgeable manner that can support urban sustainability performance in terms of both the efficiency, management, improvement, and planning of urban systems as well as the quality of life of citizens. Irrespective of the types of smart sustainable city applications, to establish context awareness functionality requires a wide variety of technologies, including sensor networks, machine learning and data mining methods, hybrid modeling and reasoning techniques, software intelligent agents/multimodal user interfaces, cloud computing platforms, mobile and wireless communication networks, and distributed middleware infrastructures. These technologies are increasingly merging to create a new generation of context-aware services in future cities.

HCI Intelligence Versus Urban Intelligence Based on Context Awareness

The notion of intelligence alluded to in pervasive computing entails that smart environments can recognize and react to people, intelligently anticipating and responding to their desires and intentions, and in which context awareness has been given a prominent role. This notion has generated a growing level of criticism over the past two decades or so. This criticism has basically questioned its feasibility in terms of the inherent complexity surrounding modeling all kinds of situations of life (based on the cognitive, affective, emotional, social, behavioral, conversational, and physical subsets of context), and challenged its added value as to transforming the way people live. The whole premise is that it is too difficult to identify and model the specifics of context, especially psychological aspects, in real life given their extreme subtlety, subjectivity, and fluidity. In addition, the failure of the original promise of intelligence points to a two-sided problem: the persistent elusiveness of ordinary human reasoning and knowing what people want and the permissiveness of the definitional looseness of intelligence in terms of what can be expected of the role and scope of artificial reasoning in context-aware interaction paradigms (Gunnarsdóttir and Arribas-Ayllon 2012). Context awareness research and development continues to grapple with the problem of what the intelligence in context-aware computing can stand for. Nonetheless, the notion of intelligence as enabled by context awareness capabilities has inspired a whole generation of scholars and researchers into a quest for the immense, fascinating opportunities enabled by the incorporation of computer/machine intelligence into our everyday lives, as well as a large body of research into new techniques and methods for enhancing the sensing, analysis, reasoning, inference, and modeling processes. These have been of extreme value to several other applications (industrial, urban, and organizational) than those directed for human users, in which these processes are inapt to handle the complexity of the nature and scope of inferences (context knowledge) generated by computationally constrained reasoning mechanisms and oversimplified models and on the basis of limited, uncertain, incomplete, or imperfect data collected through sensors. However, the issues stemming from these challenges are under scrutiny and investigation by the research community toward alternative directions (e.g., José et al. 2010), most notably situated intelligence which entails that the cognitive processes and behavior of a situated system should be the outcome of a close coupling between the system (agent) and the environment (user) (see Lindblom and Ziemke 2002). This form of intelligence entails "assisting people in better assessing their choices and decisions and thus enhancing their actions and activities," and the "quest for situated forms of intelligence is seen by several eminent scholars as an invigorating alternative for artificial intelligence research within context-aware computing" (Bibri 2015a, p. 9).

However, the emphasis in this book is on the notion of intelligence as enabled by context awareness capabilities but in relation to urban applications rather than human-inspired HCI applications. Urban intelligence in this sense involves enhancing the efficiency of energy systems, communication systems, traffic systems, transportation systems, and so on, as well as the delivery of several classes of city services (utility, health care, education, safety, learning, etc.), based mainly on the physical, situational, and spatiotemporal subsets of context. Especially, building and maintaining complex models of smart sustainable cities functioning in real time from routinely sensed data has become a clear prospect (Batty et al. 2012; Bibri and Krogstie 2017b).

2.2.1.10 Big Data Analytics

Characteristics, Techniques, and Technologies

The term "big data" is used to describe the growth, proliferation, heterogeneity, complexity, availability, temporality, changeability, and utilization of data across many application domains. These characteristic features render the processing of big data exceed the computational and analytical capabilities of standard software applications and conventional database infrastructure. In short, the term essentially denotes datasets that are too large for conventional data processing systems. Traditional analytic systems are not suitable for handling big data (e.g., Katal et al. 2013; Khan et al. 2014). This implies that big data entail the use of tools (classification, clustering, regression, and other algorithms), techniques (data mining, machine learning, statistical analysis, etc.), and technologies (Hadoop, Spark, HBase, MongoDB, etc.) that work beyond the limits of the data analytics approaches that are being employed to extract useful knowledge from large masses of data for timely and accurate decision-making and enhanced insights. As a common thread running through most of the definitions of big data, the related information assets are of high-volume, high-variety, and high-velocity, and thus require cost-effective, innovative forms of data processing, analysis, and management. While there is no canonical or definitive definition of big data in the context of smart sustainable cities, the term can be used to describe a colossal amount of urban data, typically to the extent that their manipulation, analysis, management, and communication present significant computational, analytical, logistical, and coordinative challenges. It is near on impossible to humanly make sense of, or decipher, urban big data based on existing computing models and practices. Important to note is that such data are invariably tagged with spatial and temporal labels, largely streamed from various forms of sensors, and mostly generated automatically and routinely. Regardless of the lack of agreement about the definition of big data, there seems to be consensus that big data will lead to, in light of the projected advancements and innovations, immense possibilities and fascinating opportunities in the coming years.

Big data are often characterized by a number of Vs. The main of which—identified as the most agreed upon Vs—are volume, variety, and velocity (e.g., Fan and Bifet 2013; Laney 2001). Additional Vs include veracity, validity, value, and volatility (e.g., Khan et al. 2014). The emphasis here is on the main characteristics of big data, namely, the huge amount of data, the velocity at which the data can be analyzed, and the wide variety of data types.

- Volume denotes the amount of the data generated from a large number of sources that are to be analyzed, amounting to terabytes, petabytes, exabytes, and zettabytes. The amount of data is growing exponentially in many application areas.
- Variety means the diversity of data types, such as document-oriented and relational databases, research studies, social networking posts, mobile records, text, video, audio, images, graphs, and web content, i.e., a variety of structured, semistructured, and unstructured data.
- Velocity signifies the speed or pace at which the data flowing or arriving continuously from many different sources need to be created, processed, and analyzed. Here, time-sensitivity is of critical importance. In this regard, the data can be real-time, near real-time, periodic, streams, or batch. These entail transactions (data stored and analyzed in the past), interactions (data from websites), and observations (data collected automatically and routinely).

- Validity refers to the accuracy of the data. The issue is the possible presence of noise, error, abnormality, or bias in the data, meaning that data are not correct and thus the reliability of the results is affected. As to bias, for instance, the same dataset may be valid for one application and not so for another.
- Veracity denotes the quality of data being factually sound, i.e., their truthfulness or how certain we are about what the data claim to be. This involves the meaningfulness of the results obtained from the analysis in relation to a certain problem.
- Value entails the usefulness of the data in terms of the outcome of their analysis, as these data turn into useful knowledge by becoming highly pivotal in decision-making. Value measures how useful the data are with respect to helping in decision-making (Kaisler et al. 2013). Extracting maximum value from big data is of high interest to all kinds of organizations due to its compelling advantage associated with the ability of making decisions.
- Volatility signifies the retention policy regulating the data in different domains (e.g., urban planning, education, health care, etc.) as to their implementation. It becomes of significance with the three main Vs.

The term "big data analytics" refers commonly to any vast amount of data that has the potential to be collected, stored, retrieved, integrated, selected, preprocessed, transformed, analyzed, and interpreted for discovering new or extracting useful knowledge. This can subsequently be evaluated and visualized in an understandable format prior to its deployment for decision-making purposes (e.g., a change to or enhancement of operations, functions, strategies, designs, services, and policies). Other computational mechanisms involved in big data analytics include search, sharing, transfer, querying, updating, modeling, and simulation. In the context of smart sustainable cities, big data analytics denotes a collection of sophisticated and dedicated software applications and database systems run by machines with very high processing power, which can turn a large amount of urban data into useful knowledge for well-informed decision-making and enhanced insights in relation to various urban domains, such as transport, mobility, traffic, environment, energy, land use, planning, design, safety, health care, and education. Furthermore, the common types of big data analytics include predictive, diagnostic, descriptive, and prescriptive analytics. These are applied to extract different types of knowledge or insights from large datasets, which can be used for different purposes depending on the application domain. Urban analytics involves the application of various techniques based on data science fundamental concepts—i.e., data-analytic thinking and the principles of extracting useful knowledge (hidden patterns and meaningful correlations) from data, including machine learning, data mining, statistical analysis, regression analysis (explanatory modeling versus predictive modeling), database querying, data warehousing, or a combination of these. The use of these techniques depends on the urban domain as well as the nature of the urban problem to be tackled or solved. For example, in their prototype implementation for big data analytics in smart cities, Khan et al. (2015) apply some of the stated techniques. However, data mining is the most widely used big data analytics technique in the urban domain and presents a tremendous challenge due to the interdisciplinary and multidisciplinary nature of urban data. This pertains almost to all urban domains as areas of application.

Data processing platforms are a key component of the ICT infrastructure of smart sustainable cities with respect to big data applications. Irrespective of the application area to which big data are applied, big data analytics is associated with some kind of data processing platforms for handling the analysis and management of large datasets. Among the leading platforms for big data storage, processing, and management include Hadoop MapReduce, IBM Infosphere Streams, Stratosphere, Spark, and NoSQL-database system management (e.g., Al Nuaimi et al. 2015; Fan and Bifet 2013; Khan et al. 2015; Singh and Singla 2015). As ecosystems, they perform big data analytics related to a wide variety of large-scale applications intended for different uses associated with the process of sustainable urban development, such as management, control, optimization, assessment, and improvement, thereby spanning a variety of urban domains and sub-domains. Moreover, they are used for such tasks as implementing data mining techniques or data processing in support of the data mining techniques of data science activities.

Data Mining and Its Process, Techniques, Algorithms, and Tools

Data mining (also known as knowledge discovery) is the exploration and analysis of large masses of data for the purpose of discovering valid, novel, potentially useful, and ultimately understandable patterns in data. Specifically, it is the computational process of probing colossal datasets in order to find frequent, hidden, and previously unsuspected and unknown patterns and subtle relationships; to make useful, meaningful, and valid correlations from these discoveries; and to summarize the results in novel ways and then visualize them in understandable formats prior to their deployment for decision-making purposes. According to several codifications of the process of data mining (e.g., Provost and Fawcett 2013; Shearer 2000), this process consists of well-defined stages, namely, problem understanding, data understanding, data preparation, model building, result evaluation, and result deployment. As to the latter, the resulting knowledge can be used for supporting or automating decisions as well as for enhancing existing practices, strategies, and policies. Accordingly, data mining as the automated extraction of useful knowledge from large datasets is associated with, in the context of smart sustainable cities, advancing their contribution to the goals of sustainable development through knowledge-driven or well-informed decision-making processes pertaining to diverse urban systems and domains. In more detail, the process of data mining targets optimization and intelligent decision support pertaining to the control, optimization, management, and planning of urban systems as operating and organizing processes of urban life, as well as to the enhancement of the associated ecosystem and human services related to utility, health care, education, safety, and so on. This occurs through the implementation of simulation models, optimization strategies, and decision-taking processes. Additionally, the process targets the improvement of practices, strategies, and policies by changing them based on new trends and emerging shifts. In all, the analytical outcomes of data mining can serve to improve urban operational functioning, optimize resources utilization, reduce environmental risks, and enhance the quality of life and well-being of citizens.

The process of data mining is one of the fundamental concepts of data science. As an interdisciplinary subfield of computer science, data mining involves methods at the intersection of various other computing subfields, such as artificial intelligence, machine learning, statistical analysis, database management, pattern recognition, and data visualization. Among the data mining models used to perform data processing and analysis, functions include distributed data mining, multilayer mining, data mining from multi-technology integration, and grid-based mining (Bin et al. 2010). There are a variety of data mining algorithms that can be used to solve problems pertaining to urban sustainability, including classification (e.g., decision tree induction, Bayesian network, support vector machines, *K*-nearest neighbor, case-based reasoning, back propagation, rough set approach, and fuzzy set approach), clustering, regression, profiling, similarity matching, causal modeling, predictive link, and co-occurrence grouping. These can be solved using supervised learning methods, unsupervised learning methods, or either. Covering data mining algorithms, which would normally fill multiple books, is beyond the scope of this book. But there are many books out there addressing such algorithms from practical guides to mathematical and statistical treatments. While many data mining algorithms are exactly the embodiment of the fundamental concepts of data science, this book focuses rather on such concepts and how they help urban analysts (ideally data scientists specialized in urban analytics) to think about urban sustainability problems where data mining are brought to bear. Hence, we will refrain from providing the deep technical details of how the data mining algorithms actually work, but we will attempt to provide just enough detail so that the reader can understand what these algorithms do as a form of tasks as well as how they are based on the fundamental principles of data science.

Big data mining is associated with open source initiatives, which include the following (Fan and Bifet 2013):

- Apache Mahout: a scalable machine learning and data mining algorithm (classification, clustering, frequent pattern mining, etc.) based mainly on Hadoop architecture.
- R: a software environment and programming language intended for statistical analysis and visualization and for cluster-based scalable machine learning.
- MOA: a stream data software for real-time mining (classification, clustering, regression, frequent item-set mining, frequent graph mining, etc.) and also for cluster-based scalable machine learning.
- SAMOA: a software designed for distributed stream mining integrating S4 and Storm with MOA.
- and Pegasus: a big graph mining system used for finding patterns in massive real-world graphs and built on top of MapReduce.

- R in combination with Hadoop MapReduce (Lu et al. 2011) can be utilized for data mining in smart cities (see Khan et al. 2015).

In the context of smart sustainable cities, these software tools and applications can be used separately or combined based on the application area in terms of urban domains and sub-domains and the way these interrelate and collaborate.

2.2.1.11 Cloud Computing, Fog Computing, and Distributed Computing

The term "cloud computing" has been defined in multiple ways by ICT experts and researchers and a wide range of organizations (e.g., government agencies) and institutions (e.g., educational institutions). Common threads running through most definitions are that cloud computing denotes a computing model in which standardized, scalable, and flexible ICT-enabled capabilities delivered in real-time via the Internet in the form of three types of services: (1) software-as-a-service (SaaS), (2) platform-as-a-service (PaaS), and (3) infrastructure-as-a-service (IaaS) to external users or customers. SaaS and PaaS denote the provider's software applications and software development platforms, respectively, and IaaS means virtual servers, storage facilities, processors, and networks as resources, all being delivered over the cloud. Thus, cloud computing consists of several components, which can be rapidly provisioned with minimal management effort. However, the diversity of the definitions of, coupled with the lack of agreement over what constitutes, cloud computing has created confusion as to what it really means as an emerging computing model, and consequently its definitions have been criticized for being too broad and unclear (see Kalyvas et al. 2013a, b). Users of cloud computing, including individuals, organizations, and government agencies employ it to, as a variety of enabled services, store and share information; manage, sift, and analyze databases; and deploy Web services, including processing huge datasets for complicated problems of scientific kinds (Paquette et al. 2010). Cloud computing can also be used to process urban big data and context data in relation to smart sustainable city applications.

Fog computing (Numhauser and Jonathan 2012), also known as fogging or edge computing, can be viewed as an alternative computing model to cloud computing in the context of the IoT and its underlying big data analytics. It is an architecture that uses one or more collaborative near-user edge devices to carry out a substantial amount of storage (rather than stored primarily in cloud data centers), communication (rather than routed over the Internet backbone), control, configuration, measurement, and management (rather than controlled primarily by network gateways). Although both fog computing and cloud computing provide storage, applications, and data to end users, fog computing has a bigger proximity to end users and bigger geographical distribution (Bonomi et al. 2012). On the data plane which constitutes one of the components of fog networking, fog computing enables computing services to reside at the edge of the network as opposed to servers in a data center like in cloud computing. Accordingly, fog computing emphasizes proximity to end users and client objectives, dense geographical distribution, and local resource pooling, latency reduction and backbone bandwidth savings to achieve better quality of service (QoS) (Brogi and Forti 2017), as well as edge analytics/stream mining resulting in redundancy in case of failure (Arkian et al. 2017). Moreover, it is said that fog computing is a medium weight and intermediate level of computing power, whereas cloud computing can be a heavyweight and dense form of computing power, as it uses a network of remote servers hosted on the Internet to store, manage, and process data, rather than a local server. Mist computing is a lightweight form of computing power that resides directly within the network fabric at its extreme edge using microcomputers and microcontrollers to feed into fog computing nodes and potentially onward toward the cloud computing platforms. Furthermore, fog computing extends cloud computing to the edge of an organization or city's network. In this context, it facilitates the operation of computation, storage, communication, and networking services between end devices and cloud computing data centers, and entails the distribution of the related resources and services on or close to devices and systems in the control of end users (Zhang 2016; Ostberg et al. 1997).

Distributed computing is a field of computer science that is concerned with distributed systems. A distributed system is a model in which components located on networked computers, physically distributed within some geographical area, communicate and coordinate their actions by passing messages (Coulouris et al. 2011). In a much wider sense, it refers to autonomous processes that run on the same physical computer or networked computers and interact with each other by message passing. Regardless, the user perceives the collection of autonomous processes as a unit. In this context, each computer may have its own user with individual needs, and the purpose of the distributed system is to coordinate the use of shared resources or provide communication services to the users (Ghosh 2007). A computer program that runs on a distributed system is called a distributed program. In a distributed system, several computations execute simultaneously and potentially interact with each other in order to achieve a common goal. A distributed system extends the idea of concurrency onto multiple computers connected through a network. Computers within the same distributed system have their own private memory, and the information is often exchanged among themselves to achieve a common goal. One of the characterizations of a distributed system is that several autonomous computational entities (computers or nodes) have their own local memory and communicate with each other by message passing, to reiterate. Three significant features of distributed systems are as follows: concurrency of components, lack of a global clock, and independent failure of components (Coulouris et al. 2011). Other typical properties of distributed systems include tolerate failures in individual computers, the structure of the system (network topology, network latency, number of computers) not known in advance, the system consisting of different kinds of computers and network links, and the system changing during the execution of a distributed program, each computer with only a limited or incomplete view of the system and aware only of one part of the input (Ghosh 2007; Lynch 1996).

Distributed computing entails the use of distributed systems to solve computational problems. In distributed computing, a problem is divided into many tasks, each of which is solved by one or more computers. It is of high applicability in big data and context-aware applications as distributed systems running across different, yet related, urban domains (see Bibri and Krogstie 2017c). Distributed computing has emerged due to the fact that large-scale applications require the use of a communication network that connects several computers that may use data produced in different physical locations, which are usually required to be exchanged across these locations. Also, the use of a distributed system is beneficial for practical reasons pertaining to the very nature of big data and context-aware applications. Indeed, it is more cost-efficient to obtain the desired level of performance by using a cluster of several low-end computers, in comparison with a single high-end computer. This applies to Hadoop MapReduce compared to other big data processing platforms using one supercomputer (see Singh and Singla 2015). The common use of Hadoop MapReduce is justified by the suitability of its functionalities as to handling urban data as well as to its advantages associated with load balancing, cost-effectiveness, flexibility, and processing power compared to other data processing platforms. Hadoop MapReduce has become the primary big data storage and processing system given its simplicity, scalability, and fine-grain fault tolerance (Zhang et al. 2016). For example, it is capable of handling all data types collected from multiple sources to derive actionable insights. By involving various points of failure, a distributed system can provide more reliability than a non-distributed system. Moreover, a distributed system may be easier to expand and manage than a monolithic uniprocessor system (Elmasri and Navathe 2000).

2.2.2 The Key Constructs of the Conceptual and Theoretical Framework

The conceptual and theoretical framework is the structure that holds or supports the theory of this scholarly endeavor. Smart sustainable cities of the future can be viewed as a holistic urban development approach which seeks to explicitly bring together sustainable cities and smart cities as urban endeavors in ways that address and overcome the key shortcomings of both classes of cities in terms of their contribution to the goals of sustainable development. This occurs through merging and leveraging what each class has to offer for sustainability in terms of pervasive computing and advanced ICT (mainly from smarter cities) and design concepts and planning principles (from sustainable urban forms), with the sheer purpose of advancing sustainability in an increasingly technologized, computerized, and urbanized world (Fig. 2.1).

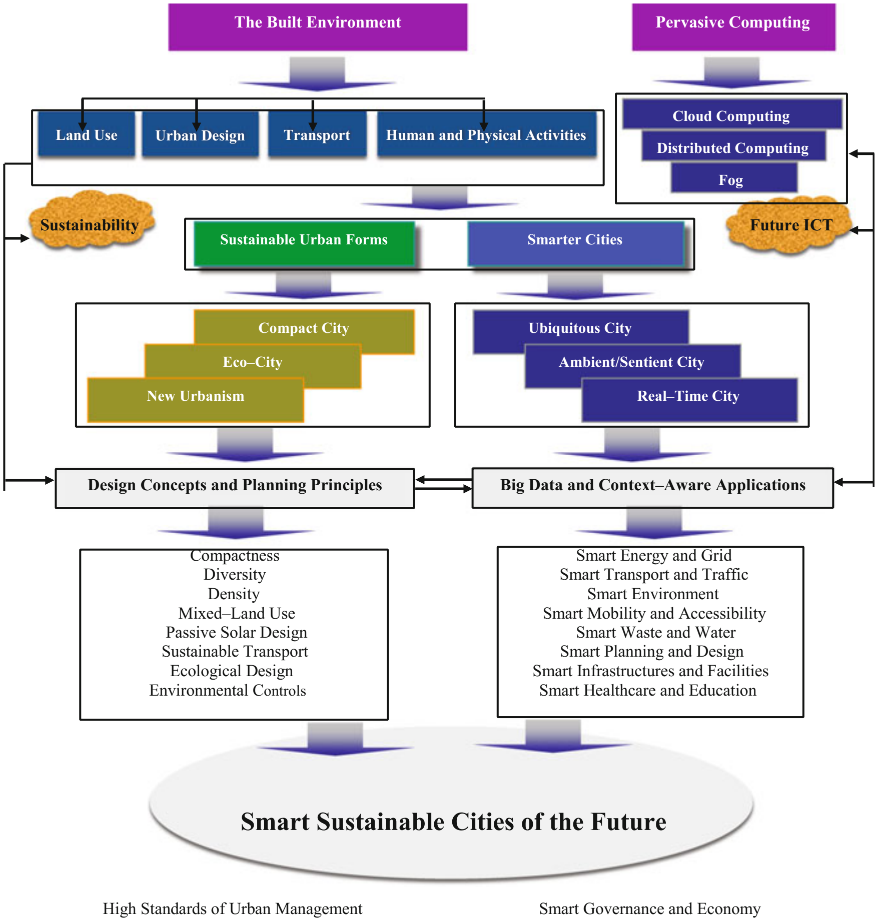

Fig. 2.1 The key constructs of the conceptual and theoretical framework

2.3 The Disciplinary Dimension of the Foundational Framework for Smart Sustainable City Development

2.3.1 On Academic Disciplines

An academic discipline, or field of study, is a branch of knowledge that is taught and researched as part of higher education or at university level. It incorporates expertise, scholars, communities, studies, research areas, research projects, and challenges that are strongly associated with a given scholastic subject area and related practice, e.g., smart sustainable cities. The scholarly discipline of smart sustainable cities is a collection of research methods and communication norms shared among a group of scholars (planners, engineers, architects, computer scientists, data scientists, ICT experts, etc.) with interests in city development. Generally, scholarly disciplines are useful for narrowing research efforts and for creating ongoing dialogues about particular subjects. Further, there is no consensus on how some academic disciplines should be classified in relation the human, social, and natural sciences. City-related disciplines (urban planning, urban design, urban sustainability, etc.) tend to be well-established and have branches, and these are often called subdisciplines. As such, they involve established knowledge directed for applied research in relation to diverse urban applications. In the context of this chapter, they provide a basis for smart sustainable city development practice as a collection of expert and scholarly knowledge, studies, research domains, practical methods, scholars, and practitioners. Therefore, the set of academic disciplines presented and discussed below are identified on the basis of their relevance to the interdisciplinary and transdisciplinary field of smart sustainable cities in terms of the knowledge underpinning their development as a set of future practices. These academic disciplines include, but are not limited to, urban planning, urban design, data science, computer science, modeling and simulation, complexity science, and sustainability science.

The intention of providing the disciplinary dimension of the foundational framework for smart sustainable city development is to enable a holistic understanding of the multifaceted phenomenon of smart sustainable cities in the pursuit of normative actions associated with implementing sustainability using ICT in future urban practices. Smart sustainable city development requires understanding of diverse academic disciplines to solve complex problems and thus facilitate practical endeavors. Also, the intention is to induce and motivate researchers to further cross boundaries between the identified disciplines to create new perspectives and insights based on interactional or unifiable knowledge beyond those disciplines—with a result that yields new ideas by thinking across boundaries or exceeds the simple sum of each discipline—by interlinking or unifying different analyses, integrating or fusing theories, and spilling over or blurring disciplinary boundaries. Pooling various disciplinary approaches together is of importance to arrive at a theoretically solid and analytically informed multi-perspective on smart sustainable city development, as well as to holisticize knowledge for enhancing practices. Besides, an interdisciplinary or transdisciplinary approach is necessary to address the complex issue of smart sustainable cities, as well as to respond knowledgeably, holistically, and critically to the most pressing issues and significant challenges of the contemporary city in terms of sustainability. In all, researchers in the domain of smart sustainable urban development could, on the basis of the provided disciplinary essentials, synthesize broad perspectives, knowledge, skills, and interconnections to create new insights, and in doing so, gain a broader understanding of the field in terms of synergies and complexities, which is necessary to enhance the practice of smart sustainable city development. The following academic disciplines have strong implications for the development of smart sustainable cities of the future.

2.3.2 Urban Planning

Institutionalized in many industrialized nations since the late nineteenth century, urban planning is a governmental function in most countries worldwide, which is practiced on neighborhood, district, city, metropolitan, regional, and national scales with land use, environmental, transport, local, metropolitan, and regional planning representing more specialized foci. Several notable books (e.g., Jacobs 1961; Lynch 1981; McHarg 1995; Mumford 1961; Wheeler and Beatley 2010) have been written on the subject of urban planning (and development). They have approached it from a variety of perspectives, often combined, including physical, spatial, social, cultural, political, economic, and ecological. Urban planning is the process of guiding and directing the use and development of land, urban environment, and urban infrastructure as well as ecosystem and human services—in ways that ensure effective utilization of natural resources, intelligent management of infrastructures and facilities, efficient operations and services, optimal economic development, and high quality of life and well-being. In more detail, urban planning involves drawing up, designing, evaluating, and forecasting an organized, coordinated, and standardized physical arrangement and infrastructural system of a city and the associated processes, functions, and services, i.e., built form (buildings, streets, residential and commercial areas, facilities, parks, etc.), urban infrastructure (transportation, water supply, communication systems, distribution networks, etc.), ecosystem services (energy, raw material, air, food, etc.), human services (public services, social services, cultural facilities, etc.), and administration and governance (implementation of mechanisms for adherence to established regulatory frameworks, practice enhancements, policy recommendations, technical and assessment studies, etc.). The ultimate aim of urban planning is to make cities more sustainable and thus livable, safe, resilient, and attractive places. As an academic discipline, urban planning is concerned with strategic thinking, research and analysis, sustainable development, environmental planning, transportation planning, land-use planning, landscape architecture, civil engineering, policy recommendations, public administration, and urban design (e.g., Nigel 2007). These areas are to be taken into account in any backcasting approach to planning for city development.

2.3.3 Urban Design

Urban design overlaps with urban planning in terms of perspectives and practices. Urban design as an interdisciplinary field involves urban planning, landscape architecture, and civil engineering (Van Assche et al. 2013), in addition to such sub-strands as sustainable urbanism, sustainable urban design, and strategic urban design. Dealing with the design and management of the public domain and the way this domain is experienced and used by urbanites, urban design denotes the process of designing, shaping, arranging, and reorganizing cities with respect to physical structures, arrangements, and typologies. The focus in sustainable urban design is on the larger scale of buildings, streets, neighborhoods, districts, parks, public infrastructure, and public spaces, with the primary aim of making urban living more environmentally sustainable and urban areas more attractive and functional (e.g., Aseem 2013; Boeing et al. 2014; Larice and MacDonald 2007; McHarg 1995). In this regard, urban design entails making connections between forms for human settlements and environmental sustainability, economic viability and social equity, the built environment and ecosystems, people and the natural environment, and movement and urban form. These issues are also of interest to the field of urban planning. In the context of this chapter, the emphasis is on the smart planning of sustainable urban forms as a set of integrated typologies and design concepts (namely, density, compactness, diversity, mixed-land use, sustainable transport, and ecological design) as organized, coordinated, and standardized physical arrangements and spatial organizations. The way cities are designed and planned is of paramount importance to sustainable development and thus sustainability (e.g., Egger 2006). McHarg (1995) describes and illustrates an ecologically sound approach to urban planning and design, and Wheeler and Beatley (2010) provide a range of perspectives on sustainable urban planning and development.

2.3.4 Data Science

Data science is a flourishing field, and its particular concerns are relatively new and its general principles are just materializing. Its ultimate goal is to enhance decision-making pertaining to a large number and variety of domains through the practice of basing decisions on the analysis of data—data-driven decision-making (DDD). Yet, data science requires a careful thinking about what kind of available data might be used and how these data can be used depending on the application domain, specifically in terms of the problem that is to be tackled. It assumes access to and utilization of large masses of data and often benefits from sophisticated data engineering facilitated by data processing and other software technologies being in use within a wide variety of organizations and institutions. In the context of smart sustainable cities, data science involves principles, processes, and techniques incorporated in cutting-edge technologies distributed across diverse urban entities for understanding and analyzing urban problems and phenomena in relation to environmental, social, and economic sustainability via the automated analysis of urban data, coupled with specialized knowledge, creativity, and common sense of data scientists. Accordingly, data science-oriented analytic thinking enables one to evaluate urban sustainability proposals for data mining projects in the context of smart sustainable cities. If a planner, strategist, or expert proposes to improve a particular energy, traffic, environment, or healthcare application by extracting knowledge from urban data, it is crucial for the data scientist (or urban analyst) to be able to assess the proposal systematically and decide whether and why it is sound or flawed. This concerns identifying obvious weak spots, unrealistic assumptions, and unconnected and missing pieces rather than determining whether it will actually succeed.

The fundamentals of data science as a set of unified concepts, principles, and techniques incorporated in data science technologies underlie big data analytics techniques—e.g., data mining as a process of extracting useful knowledge from data for enhanced decision-making and insights. In organizing thinking and analysis, these fundamentals make it possible to deeply understand data science approaches and processes instead of focusing in depth on the wide range of specific data mining algorithms (Provost and Fawcett 2013). Compared to other big data analytics techniques, coupled with the fact that data science is of wider application than the use of data mining, data mining algorithms provide the most explicit illustrations of data science fundamentals, which differ from, and are complementary to, statistics and database querying. However, in the context of smart sustainable cities, it has become important to foster the ability to approach urban sustainability problems "data-analytically," as well as to assess how urban data can improve sustainability performance in relation to diverse urban domains. This implies that the knowledge extracted from large bodies of urban data is assumed to be in the form of nontrivial, actionable models. This entails applying a set of fundamental concepts that facilitate careful urban data-analytic thinking, understanding data mining techniques and data science applications in relation to sustainability dimensions, and developing relevant frameworks for structuring urban thinking about data analytics (sustainability) problems so that it can be done systematically.

2.3.5 Computing and Computer Science

Generally, computing can be defined as: "any goal-oriented activity requiring, benefiting from, or creating computers. Thus, computing includes designing and building hardware and software systems for a wide range of purposes; processing, structuring, and managing various kinds of information; doing scientific studies using computers; making computer systems behave intelligently; creating and using communications and entertainment media; finding and gathering information relevant to any particular purpose, and so on. The list is virtually endless, and the possibilities are vast" (ACM, AIS and IEEE-CS 2005, p. 9). Computing involves computer science, computer engineering, information technology, information systems, and software engineering. These five subdisciplines constitute the field of computing (ACM, AIS and IEEE-CS 2005). As subdomains of scientific research, they have many overlaps among them in their theories, methodologies, and practices since they form the domain of computing.

Computer science is concerned with the study of the theoretical foundations of information (e.g., structures, representation) and computation (e.g., mechanisms, algorithms) and the practical techniques and methods for their implementation in computer systems (Bibri 2015b). In other words, it is the scientific and practical approach to computation and its applications and the systematic study of the feasibility, structure, expression, and mechanization of the methodical procedures that underlie the acquisition, representation, storage, processing, analysis, communication of, and access to information. In short, it is the study of the theory, experimentation, and engineering that form the basis for the design and use of computer systems. As a discipline, computer science spans a range of topics from theoretical studies of algorithms and the limits of computation to the practical issues of implementing computing systems in hardware and software (CFCS 2004).

Computer scientists deal with the systematic study and development of algorithmic processes that describe, create, and transform information and formulate abstractions (or conceptualizations) to model, simulate, and design complex systems (Denning et al. 1989; Wegner 1976). They, therefore, specialize in the theory of computation and the design of computational systems. A number of computer scientists argue for the distinction of three separate paradigms in computer science. Wegner (1976) argues that those paradigms are science, technology, and mathematics. Denning et al. (1989) argue that they are theory, abstraction (modeling), and design. Eden (2007) describes them as the "rationalist paradigm" (which treats computer science as a branch of mathematics, which is prevalent in theoretical computer science and mainly employs deductive reasoning), the "technocratic paradigm" (which is found most prominently in software engineering), and the "scientific paradigm" (which approaches computer-related artifacts from the empirical perspective of natural sciences, identifiable in some branches of artificial intelligence).

Its fields can be divided into a variety of theoretical and practical disciplines, including computational complexity theory, programming language theory, computer programming, human–computer interaction, and artificial intelligence. In more detail, there are several areas that are crucial to the discipline of computer science, including theory of computation, algorithms and data structures, programming methodology and languages, and computer elements and architecture, in addition to software engineering, artificial intelligence, computer networking and communication, database systems, parallel computation, distributed computation, human–computer interaction, computer graphics, operating systems, and numerical and symbolic computation.

Among the areas of computing science that underpin smart sustainable city development practice in terms of computational systems include the following:

Data structures and algorithms: The study of commonly used computational methods and their computational efficiency. They are of relevance to the functioning of big data and context-aware applications in the context of smart sustainable cities (Bibri and Krogstie 2017c). Big data analytics and context-aware computing should involve highly sophisticated and dedicated techniques and algorithms associated with machine learning, data mining, statistics, database query, and so on that can perform complex computational processing of data for timely and accurate decision-making purposes. New approaches to storing, managing, coordinating, and analyzing big data and processing context information, in particular in relation to smart sustainable city applications should rely on advanced artificial intelligence programs. For a detailed account of big data analytics and context-aware computing techniques and algorithms from a general perspective, the interested reader might want to read Provost and Fawcett (2013) and Bibri and Krogstie (2017c), respectively.

Theory of computation: Deals with the fundamental question underlying computer science: "What can be (efficiently) automated?" (Denning 2000). Theory of computation is focused on answering fundamental questions about what can be computed and what amount of resources are required to perform those computations. This is of particular relevance to many urban problems in the sense of using computability theory to examine which are computationally solvable on various theoretical models of computation (see Bettencourt 2014 for illustrative examples of computationally intractable problems in the context of smart sustainable cities). As regards to defining critical problems relating to smart sustainable cities, ICT is focused on defining critical problems that emerge rapidly and unexpectedly, some of which reveal critical infrastructures. The analysis of such problems and their identification is crucial to the sustainability of smart sustainable cities. These are far from equilibrium, dominated by fast and slow dynamics in short and long cycles (e.g., Batty et al. 2012).

Concurrent, parallel, and distributed systems: In such systems, several computations execute simultaneously and potentially interact with each other. A distributed system extends the idea of concurrency onto multiple computers connected through a network. Computers within the same distributed system have their own private memory, and the information is often exchanged among themselves to achieve a common goal. This relates to cloud computing and fog computing as models for performing big data analytics and context-aware computing in relation to diverse applications in the context of smart sustainable cities. Part of the process of coordination and integration using state-of-the-art data systems and distributed computing must involve ways in which the citizenry is able to participate and to blend their personal knowledge with that of experts who are developing these technologies (Batty et al. 2012).

Computer network: Aims to manage networks between computers across different geographical areas. This is of high relevance to urban domains in the context of smart sustainable cities. To develop technologies that ensure widespread participation, new ICT is essentially network-based and enables extensive interactions across many domains and scales (Batty et al. 2012). Wireless network technologies include satellite-enabled GPS, mobile phone, LPWAN, and Wi-Fi networks for collecting and coordinating data in terms of the data themselves and how that data are stored and made accessible. ICT of pervasive computing will result in a blend of smart applications enabled by constellations of instruments across many spatial scales linked via multiple networks for providing continuous data flowing from various urban domains (processes, activities, movements, interactions, observations, etc.), This can provide a fertile environment conducive to advancing the contribution of smart sustainable cities to sustainability over the long run by monitoring, understanding, analyzing, and planning them in ways that strategically assess, improve, and sustain this contribution through the design and planning principles of sustainability.

Computer security: Aims to protect information from unauthorized access, disruption, or modification while maintaining the accessibility and usability of the system for its intended users (see Chap. 8 for further discussion on different aspects of information security as part of risk management in the context of smart sustainable cities). It is highly important to ensure that all technological components associated with big data and context-aware applications for smart sustainable cities are supported by security measures. Massive repositories of urban data are at stake, and failure to protect these data will pose risks and threats to the functioning of such applications, as well as to the safety and well-being of citizens. Therefore, security measures should be at the center of urban policy and governance practice associated with the design, development, deployment, and implementation of big data and context-aware applications within smart sustainable cities. Any attempt of an unauthorized access, malicious attack, or abuse of information on citizens, infrastructures, networks, and facilities can compromise the integrity of such applications and related services. Smart sustainable cities generate colossal amounts of data on virtually every urban process, which must be securely maintained for processing, analysis, and sharing. Urban environments are now being continually forged in sensorial, informational, and communicative processes. It is a world where smart sustainable cities think of us, where the environment reflexively monitors our behavior, including the extent to which we behave in a sustainable way through the activities and processes we perform on a daily basis.

Human–computer interaction (HCI): a common thread running through most definitions of HCI is that it deals with the study, development, and implementation of the interaction between users and computers. The Association for Computing Machinery defines HCI as “a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them” (ACM SIGCHI 2009). HCI is the process of communicating information from or presenting services by computer systems via display units to human users as a result of the manipulation and control of such systems by means of explicit or implicit input devices. Its special concerns include the joint performance of tasks by users and computers; the structure of communication between users and computers; human capabilities to use computers; algorithms and programming of user interfaces; engineering issues relating to designing and building interfaces, the process of analysis, design, and implementation of interfaces; and design trade-offs (ACM SIGCHI 2009). HCI also deals with enhancing usability and learnability of interfaces; techniques for evaluating the performance of interfaces; developing new interfaces and interaction techniques; developing and applying design methodologies to real-world problems; prototyping new software and hardware systems; exploring new paradigms for interaction (e.g., natural interaction); and developing models and theories. As to developing new technologies for communication and dissemination, new sources of urban data, the articulation of urban problems, plans and policies, and all the apparatus used in engaging the community in developing smart sustainable cities require new forms of online participation making use of the latest ICT in terms of state-of-the-art HCI and distributed computation (Batty et al. 2012).

Artificial Intelligence: Is concerned with understanding the nature of human intelligence, and creating computer systems capable of emulating human intelligent behavior. Therefore, it involves the modeling and simulation of intelligent cognitive and behavioral aspects of humans into machines, such as learning, reasoning, problem-solving, perception, learning, planning, creativity, language, language production, actuation, decision-making, and so forth. John McCarthy, who coined the term in 1956, defines it as "the science and engineering of making intelligent machines" (McCarthy 2007). While there are many definitions of artificial intelligence in the literature, a common thread running through all definitions is the study of cognitive phenomena or the simulation of human intelligence into machines. Implementing aspects of human intelligence in computer systems is one of the main practical goals of artificial intelligence. Computer intelligence combines a wide range of advanced technologies, such as machine learning, data mining, artificial neural networks, multisensory devices, data fusion techniques, modeling techniques (knowledge representation and reasoning), natural user interfaces, computer vision, and intelligent agents. These areas are at the core of context-aware computing and big data analytics as a set of technologies and their novel applications that are directed for use within diverse urban domains to advance sustainability in the context of smart sustainable cities (Bibri and Krogstie 2017c).

Software engineering: Is the study of designing, implementing, and modifying software in order to ensure it is of high quality, affordable, maintainable, and fast to build. It is a systematic approach to software design, involving the application of engineering practices to software. It deals with the creation, organization, analysis, and maintenance of software. Engineering computer applications software and computer systems software are at the heart of smart sustainable city development in terms of big data applications and context-aware systems (see Chap. 8 for a detailed account of software development activities as part of project management associated with urban complexity).

2.3.6 Modeling and Simulation

Modeling and simulation is an emerging discipline that is based on developments in diverse computer science areas, as well as influenced by developments in systems theory, complexity science, data science, and systems engineering. This foundation brings elements of art, science, engineering, and design together in a complex and unique way that requires domain experts to enable appropriate decisions when it comes to the application or development of modeling and simulation methods in the context of smart sustainable cities. Padilla et al. (2011) recommend to distinguish between modeling and simulation science, engineering, and applications.

- Modeling and simulation science contributes to the underlying theory, defining the academic foundations of the discipline.
- Modeling and simulation engineering is rooted in theory but looks for applicable solution patterns. The focus is general methods that can be applied in various problem domains.
- Modeling and simulation applications solve real-world problems by focusing on solutions using modeling and simulation methods. Often, the solution results from applying a method, but many solutions are very problem domain specific and derived from problem domain expertise and not from any general modeling and simulation theory or method.

Modeling and simulation as concepts are often used interchangeably, or as synonyms within disciplines. However, within the discipline of modeling and simulation, these concepts are treated as distinctive and equally important concepts. Modeling is understood as the purposeful abstraction of reality, resulting in the formal specification of a conceptualization and underlying assumptions and constraints. Modeling and simulation involves models that are used to support the implementation of an executable version on a computer over time. In short, modeling focuses mainly on conceptualization, residing on the abstraction level, and simulation mainly on implementation, residing on the implementation level.

In more detail, modeling and simulation is the use of models—i.e., physical, mathematical, computational, or logical representation of a system, phenomenon, or process—as a basis for simulations—i.e., methods for implementing a model to develop data as a basis for decision-making pertaining to planning, management, design, and so forth, i.e., city planning and development. In this regard, management and engineering knowledge and guidelines are needed to ensure that conceptualization and implementation—modeling and simulation—are well connected for related activities are mutually dependent, although they can be carried out by separate professionals (modelers and simulysts). As the role of big data analytics continues to grow, the role of combined simulation of analysis is an emerging domain within city development—in order to blend algorithmic and analytic techniques as part of the process of data mining through visualizations available directly to planners, analysts, and decision-makers. In the context of smart sustainable cities, the modeling and simulation process entails creating and analyzing digital prototypes of physical, infrastructural, environmental, socioeconomic, spatiotemporal, operational, and functional models in terms of how they operate, interrelate, coordinate, and affect one another to identify and predict dynamic changes in the underlying behavioral patterns due to some kind of reciprocal relationships cycling to produce the kind of patterns that smart sustainable cities might exhibit as a result of their functioning, adaptation, and development in relation to sustainability. This allows to determine and forecast potential problems in the real world, and to look at more effective ways to overcome or eradicate them. In this regard and context, complex system modeling and simulation denotes the operation of the whole model of the system (smart sustainable city and its subsystems) to evaluate the performance of the system behavior as regards to sustainability, and allows to adjust any parameters within the system under investigation and then to optimize the system to increase success in terms of enhancing different aspects of sustainability across various urban domains. This involves alterations in such domains in terms of operations, functions, designs, services, strategies, and policies, as well as in how these domains interrelate and are coordinated.

As such, modeling and simulation can facilitate understanding smart sustainable cities' behavior or some of their subsystems' without actually testing or instantiating them in the real world. However, to ensure that the results of simulation are applicable to the real world, it is necessary to understand the assumptions, conceptualizations, and implementation constraints of modeling and simulation as an emerging field. Only then could useful insights about different decisions in the design, development, management, and planning of smart sustainable cities be gleaned without actually developing the city or some of its components. This is of crucial importance to save financial, physical, social, and human resources that would otherwise be huge and expensive in relation to the development, deployment, and implementation of the actual city. In addition, simulation can support experimentation (e.g., the use of innovative technologies, the coordination of urban domains, the integration of urban systems, etc.) that occurs totally in software environments where simulation represents systems or generates data needed to meet experiment objectives. The use of modeling and simulation within city planning and development is well recognized (e.g., Batty et al. 2012). Simulation technology belongs to the tool set of planners, engineers, and architects within most urban application domains. In all, modeling and simulation helps to reduce costs, save resources, increase the quality and performance of systems, and document and archive lessons learned.

Simulation methods have great potential to revolutionize the smart sustainable city development in the future. Among the reasons for the increasing interest in simulation applications are the following:

- Using simulations is generally cheaper, safer, and faster than conducting real-world experiments or studying real-time processes or events.
- Simulations allow the flexible configuration of the parameters within different sub-processes found in the operational application field of smart sustainable cities as complex systems.
- Simulations enable efficient if-then-else analyses of different alternatives, in particular when the necessary data to initialize the simulation can easily be obtained from operational data (energy, environment, transport, mobility, etc.). This use of simulation relies on decision support simulation systems, which is at the core of the functioning of smart sustainable cities as an amalgam of interrelated processes.

Modeling and simulation is important within research in the field of smart sustainable cities of the future. Representing the real systems either via physical reproductions at smaller scale, or via mathematical or computational models that allow representing the dynamics of the city via simulation (see, e.g., Batty et al. 2012; Bibri and Krogstie 2017b), allows exploring system behavior in an articulated way which is often either not possible, too expensive to deploy, or too risky in the real world. Modeling and simulation is a key enabler for engineering activities associated with complex systems such as smart sustainable cities in terms of their design and planning, as the computational representation of the system as a model enables planners and engineers to reproduce the system behavior. A collection of applicative modeling and simulation methods to support systems engineering activities is provided in (Gianni et al. 2014).

One of the existing taxonomies of modeling and simulation that is of relevance to smart sustainable city development is the following:

- Analyses support is conducted in support of urban planning and design. Very often, the search for an optimal solution (e.g., integration of design concepts and typologies with big data and context-aware applications to advance sustainability) that shall be implemented is driving these efforts. What-if analyses of alternatives fall into this category as well. This sort of work is often accomplished by simulysts. A special use of analyses support is applied to urban operations. Simulation systems improve the functionality of their decision support systems by adding the dynamic element, as well as allow to compute estimates and predictions, including optimization and what-if analyses.
- Systems engineering support is applied for the development and testing of systems (energy, transport, traffic, etc.). This support can start in early phases and include topics like executable system architectures. And it can support testing by providing a virtual environment in which tests are conducted. This sort of work is often accomplished by engineers and architects.

2.3.7 Complexity Science (And Complex Systems)

As an emerging approach to research and a multidisciplinary subject, complexity science is the scientific study of complex systems, systems composed of many parts connected and joined together by a web of relationships that interact to generate collective behaviors that cannot easily be explained on the basis of the interaction between the individual constituent elements. Accordingly, complexity entails the way a vast number of complicated and dynamic sets of relationships, interactions, or dependencies can produce some behavioral patterns. Complexity science is a set of conceptual tools and theories from an array of disciplines (Benham-Hutchins and Clancy 2010; Paley and Gail 2011). It deals with complex systems as a collection of interconnected parts and relationships that are dynamical, unpredictable, and multidimensional in nature. It has been discussed in both natural and social sciences. In a wide range of complex systems that are on focus within these sciences, computational modeling, as based on mathematical developments and modeling approaches from physics, is undertaken to study the behavior of such systems to better understand them. Software engineering expertise can be used to apply new results as well as to inspire new approaches (Batty et al. 2012). Complex systems are characterized by nonlinearity and thus require more than simplistic linear thinking, as they feature a large number of interacting elements (patterns, agents, processes, etc.) whose aggregate activity (behaviors, relationships, interactions, etc.) does not emanate from the summations of the activity pertaining to the individual elements. As such, they typically exhibit hierarchical self-organization under some kind of selective pressures. Examples of complex systems are cities, ecosystems, organisms, global climate, neural network, human brain, ICT network, and ultimately the entire universe.

As an approach to science, complex systems investigates how the dependencies, relationships, or interactions between the system's parts give rise to its collective behaviors, and how the system interacts and forms relationships with its environment (Yaneer 2002). So, it is chiefly concerned with the behaviors and properties of systems. As a research approach, it involves problems in many diverse disciplines, including information theory, computer science, mathematics, statistical physics, biology, ecology, nonlinear dynamics, sociology, and economy. As an interdisciplinary domain, it draws on theoretical contributions and perspectives from these disciplines, e.g., spontaneous order from the social sciences, chaos from mathematics, cybernetics from technology, self-organization from physics, adaptation from biology, and many others. The concerns that complexity science addresses have grown out of investigations from a varied intellectual ancestry, including cybernetics, general systems theory, chaos theory in dynamical systems, complex systems, mathematical systems, and complex adaptive systems (social systems, technological systems, urban systems, etc.) where the parts actively change the way they interact. The increased use of computer simulation created research in the simulation of adaptive behavior in the 1990s. From 2000s and onward, complexity science takes stock of what has been accumulated as substantive knowledge of all this rich background of work. A key part of the current emphasis of complexity science is its application to practical technological and engineering systems in that control systems need to be designed, managed, and constructed as they proliferate and increase in size and connectivity in a variety of contexts, e.g., smart sustainable cities. It is desirable to have the ability to build systems that are scalable, robust, and adaptive by using such properties as self-organization, self-adaptation, self-regulation, self-repair, and evolution as a way of mimicking biological systems. Complexity science is a subject of study that is well positioned to bringing together deep scientific questions pertaining to sustainability and urbanization with application-driven goals across the field of smart sustainable cities. Its contemporary applications are complemented by a rich background of theoretic work.

Complexity science touches on all facets of science and technology, creating lots of new opportunities and horizons in research. Important to underscore is that complexity is not just determined by the large number of parts of a system with very intricate design, but rather by such dynamical properties as self-organization, spontaneous order, adaptation, emergence, feedback loops, and nonlinearity. In the context of smart sustainable cities, technological and engineering systems based on big data analytics and context-aware computing are primarily designed to minimize these tricky dynamical properties. These can make smart sustainable cities as systems difficult to design, predict, and control. However, if desirable emergent behaviors and processes can be managed, harnessed, and exploited, they can allow to move beyond the limits of conventional technological and engineering systems that are merely complicated. Apart from that, we are dealing with the traditional approach to tackling complexity, which aims to reduce or constrain it and thereby typically involves compartmentalization: dividing a large system into separate parts. Technological and engineering systems are susceptible to failure for they are often designed using modular components, and where failure stems from the potential issues arising to bridge the divisions.

Dynamical properties such as feedback loops, adaptation, nonlinearity, emergence, networks, and spontaneous order as specific concepts important to complex systems originate in systems theory. Complex systems is indeed a subset of systems theory. Accordingly, both complex systems and general systems theory focus on the collective or system-wide properties and behaviors of interacting entities. But the latter is concerned with a much broader class of systems, including linear systems where the effect is directly proportional to cause, or noncomplex systems where reductionism may hold viable. Indeed, as mentioned above, systems theory entails the ordered arrangement of knowledge accumulated from the study of all classes of systems in the observable world. As such, it seeks to describe, explain, and explore all categories of systems, and one of its objectives is the invention of classes that are of value to researchers across a wide variety of fields. Generally, given the link between systems theory and complex systems, the former provides two key contributions to the latter: (1) an interdisciplinary perspective in that shared properties linking systems across disciplines justify the quest for modeling approaches applicable to complex systems across those disciplines, and (2) an emphasis on the way in which system's components interact and depend one on another can determine system-wide properties that produce collective behaviors.

2.3.8 Sustainability Discipline

2.3.8.1 Sustainability Science

Sustainability has theoretical foundations from which it has grown that have solidified into a defined science (Lee 2000). The focus in science is on general truths and laws as well as on particular methods of enquiry. As a flourishing academic discipline, sustainability science has emerged in the early 2000s (e.g., Kates et al. 2001; Clark 2007; Clark and Dickson 2003). Sustainability science is concerned with "advancing knowledge on how the natural and human systems interact in terms of the underlying (changing) dynamics, with the purpose of designing, developing, implementing, evaluating, and perennially enhancing engineered systems as practical solutions and interventions that support the idea of the socio-ecological system in balance, as well as nurturing and sustaining linkages between scientific research and technological innovation and policy and public administration processes in relevance to sustainability" (Bibri and Krogstie 2017a, p. 6). Just like the definition of sustainability, consensual definition of sustainability science is difficult to pin down. Kieffer et al. (2003, p. 432) define sustainability science as "the cultivation, integration, and application of knowledge about Earth systems gained especially from the holistic and historical sciences…coordinated with knowledge about human interrelationships gained from the social sciences and humanities, in order to evaluate, mitigate, and minimize the consequences…of human impacts on planetary systems and on societies across the globe and into the future." As a transdisciplinary field, it brings together disciplines across the natural sciences, social sciences, and applied and engineering sciences. This implies that solutions to the problems, especially those of a wicked nature, are to be grounded in the recognition that the world becomes more integrated, more complex, and more uncertain. Transdisciplinary approach remains the most relevant approach to look at smart sustainable cities as complex problems, as it insists on the fusion of different elements of a set of theories with a result that exceeds the simple sum of each, to reiterate. Understanding the tenets of several pertinent (systems) theories allows a more complete understanding of smart sustainable cities. The intent should be to set side-by-side elements of a set of theories that have clear implications for the concept and development of smart sustainable cities.

As a research field, sustainability science probes the complex mechanisms involved in the profound interactions between social, environmental, and engineered systems to understand their behavioral patterns and thus changing dynamics, in order to develop upstream solutions for tackling the complex challenges associated with the systematic degradation of these systems and concomitant perils to human well-being. That is, challenges that imperil the integrity of the planet's life support systems and compromise the future of human life. In short, sustainability science centers around the interactions between the resource system, the human system, and the governance system, and in doing so, attempts to identify and solve potential problems through devising holistic solutions. This research field seeks to give the "broad-based and crossover approach" of sustainability a solid scientific foundation. It also provides a critical and analytical framework for sustainability (Komiyama and Takeuchi 2006), and "must encompass different magnitudes of scales (of time, space, and function), multiple balances (dynamics), multiple actors (interests), and multiple failures (systemic faults)" (Reitan 2005, p. 77). In addition, sustainability science can be viewed as "neither 'basic' nor 'applied' research but as a field defined by the problems it addresses rather than by the disciplines it employs; it serves the need for advancing both knowledge and action by creating a dynamic bridge between the two" (Clark 2007, p. 1737). In all, sustainability science can be viewed as an instance of systems science.

From a broader perspective of sustainability science, some views highlight the need to probe the root causes of the fundamental unsustainability of the predominant paradigms of technological, economic, and societal development. In this line of thinking, Bibri (2015b) provides an analytical account of the implications of ICT of pervasive computing as a form of advanced science and technology for environmental and societal sustainability. Brown (2012) contends that sustainability science must involve the role of technology in as well aggravating the unsustainability of social practices (e.g., urban development) as in tackling the problems such practices generate (environmental risks), and also include the study of the societal structures as to material consumption (see Chap. 9 for a detailed account and discussion of the environmental risks posed by ICT).

To grasp the integrated whole of the socio-ecological system in terms of the complex social and multidimensional environmental characteristics, behavioral patterns, relationships, interactions, and dynamics to solve the underlying problems necessitates globally integrated political consensus and collaboration between institutional, social, economic, scientific, and technological disciplines, as well as the active engagement of citizens, communities, organizations, and institutions. One key mission of sustainability science as a more disciplined framework is to aid in coordinating cross-disciplinary integration necessary as a critical step toward a global joint effort and concerted action. In addition, the way in which sustainability science as a scholarly community can best contribute to the understanding and implementation of the goals of sustainable development should be based on an in-depth critical analysis and evaluation through scenario analysis, scientific research, technological innovation, stakeholder relationships, participatory decision-making, and policy recommendations and impacts. In a nutshell, to achieve these goals requires taking an all-inclusive approach by mobilizing diverse actors, factors, and resources. Such an analysis and evaluation should be at the core of any backcasting approach as strategic planning tool for smart sustainable city development.

2.3.8.2 Sustainable Development and Its Scientific Orientation

The link between sustainable development and science stems from the idea that the former is an aspiration that should, as realized by several scholars over the past decade, be achieved only on the basis of scientific knowledge. This has justified the establishment of a new branch of science due to the fact that, arguably, humanity is confronted at an ever unprecedented rate and larger scale with the ramifications of its own success as a species. The way things have changed in recent years (and the attempts being undertaken to take this into account) calls for a scientific approach to understanding the underlying web of ongoing, reciprocal relationships in the process of cycling to generate the patterns of behavior that the ecosystems are exhibiting, and to figuring out the mechanisms these ecosystems are using to control themselves. The point is that the complexities, uncertainties, and hazards of the human adventure are triggering unprecedented changes increasingly requiring insights from all the sciences to tackle them if there is a shred of seriousness about the aspiration to enhance and sustain the quality of life (sustainable development). The real challenge stemming from the fragmented character of science lies in understanding and acting upon the causal mechanisms and behavioral patterns in response to reciprocal relationships between different complex systems across several time and space scales. This calls for fusing disciplines and theories, a transdisciplinary approach that reconciles and amalgamates the theoretical and practical knowledge, the quantitative and qualitative perspectives, and the natural and social sciences. Sustainability science is what such an integrative approach entails, and whose emphasis is on understanding changes in states rather than just their characterization. Systems theory and system analysis approaches become the most coherent expression of this insight (Bossel 2004). Sustainability science is perhaps the most clear and desirable illustration of the endeavor of reinforcing the unified approaches and unifying tendencies in science, as well as of liberating the study of real-world processes from the boundaries between the scientific disciplines (de Vries 2013).

2.4 The Discursive Dimension of the Foundational Framework for Smart Sustainable City Development

2.4.1 On Discourse and Its Role in Engineering Social Action

2.4.1.1 Understanding Discourse

Underlying the term "discourse," in this context, is the idea that language as a form of discursive practice is structured according to a system of statements (e.g., what can be said about smart sustainable cities) used by people (e.g., urban planners, ICT experts, data scientists, researchers, policymakers, and institutions) as a particular way of understanding, talking about, and producing a particular kind of knowledge about the urban world (e.g., the physical, spatial, environmental, economic, and social dimensions of the city), as well as taking part in different domains of urban life (e.g., urban planning, urban design, urban research, urban sustainability, applied urban science, and urban analytics). Discourse, as defined by Foucault (1972), refers to: ways of constituting knowledge, together with the social practices, forms of subjectivity and power relations which inhere in such knowledge and relations between them. In short, discourses are practices which form the object that discourses talk about (Foucault 1972). In this regard, they constitute the conditions of possibility for the kind of socially anchored and institutionalized practices. And the object takes the form of a coherent set of ideas, concepts, terminologies, claims, assumptions, categorizations, visions, and prospects pertaining to smart sustainable cities that are constructed, reconstructed, transformed, and challenged in urban planning and development practices, and that through which meaning is given to smart sustainable cities as an amalgam of physical, spatial, infrastructural, operational, functional, ecological, and social systems supported with advanced ICT.

2.4.1.2 Discursive and Social Practices

Our understanding of virtually all aspects of social life is based on some kind of discourses: this is the way we make sense of, or ascribe meaning to, the world around us. Indeed, discourses are at the core of social constructionism, which develops understandings about the world that constitute the basis for shared assumptions about reality. Social reality "is produced and made real, i.e., social and political actions are engineered and become meaningful, through discourses, and social interactions with their various forms of social processes cannot be utterly understood without reference to the discourses that give them meaning and form" (Bibri 2015b, p. 39) in the first place. In other words, the constitution of social life occurs through discursive practices. A discursive practice refers to the process through which (dominant) reality comes into being (Foucault 1972). Here, practice is not meant to be understood as the opposite of theory; instead, practice involves activities that people engage in, deliberately, with the goal of developing knowledge and skills. It also denotes the construction and reflection of social realities through actions. The basis of a discursive practice approach is the insistence that discourse is action and not merely representation. In this regard, meaning is negotiated in interaction, rather than is present once-and-for-all in our utterances. Foucault was concerned with the "discursive practices" of particular epistemes, that is, those actions taken as part of the "real-world" application of discourses (see Foucault 1977). In essence, he agreed with the adage that "knowledge is power," arguing that power is implicated in the manner in which certain knowledge is applied (Hall 1997). Foucault (1972) explored the manner by which a discourse is applied to the social world, focussing on the institutional apparatuses and their technologies (e.g., the systems of thought, the rules, the institutions, the subjects, and the things). These together comprise particular discursive formations: the regularities that produce discourses (e.g., scientific disciplines). Accordingly, sociocultural reproduction and change take place through discursive practices (e.g., Foucault 1972; Phillips and Jørgensen 2002). This means that discourses produce knowledge through language use and meaning construction, and thus entail how this knowledge is institutionalized and conventionalized, thereby shaping social practices and setting new ones into play. On this note, Foucault (1972) asserts that all social practices have a discursive aspect because they involve meanings that shape and influence our actions. In a nutshell, there is a dialectical relationship between discourse and social practice. Certain social practices become legitimate forms of actions from within discourse as a system of understanding the world, and these practices, in turn, reproduce and support the discourse which legitimates them in the first place. Constructionist worldview posits that particular understanding of the world leads to particular social actions, whereby some forms of actions become unthinkable. For example, the discourse of ICT for sustainable urban development reshapes the actions of urban planners and policymakers as societal actors, as well as the meanings these actors ascribe to their endeavors. However, particular discursive constructions and the position contained with discourses open up and close down opportunities for actions by constructing particular ways of seeing the world and positioning an array of subjects within them in particular ways (see Bibri 2015b for an analytical account of subject positioning in discourse). Next, the main academic discourses associated with smart sustainable city development as a form of social practice are introduced, described, and discussed, and also some linkages between them are emphasized.

2.4.2 Academic Discourses

Scholars talk about different types of discourses: argument, narration, explanation, and description. Academic discourse is a privileged form of argument in the modern world, offering a model of rationality and detached reasoning (Hyland and Bondi 2006). It refers to the ways of thinking, using language, and producing meaning which exist in academic institutions. In other words, it is the specific style of communication used in the academic world. As such, it involves how we alter our communication (e.g., textbooks, dissertations, research articles, scientific reports, lectures, etc.) when engaged in academic discussions. Thus, it is seen to depend on the demonstration of absolute truth, empirical evidence, or flawless logic, representing what Lemke (1995) refers to as the discourse of truth. It provides an objective description of what the natural and human world is actually like, and this, in turn, serves to distinguish it from the socially contingent. This form of persuasion, which involves the use of language to relate independent beliefs to shared experience, is seen as a guarantee of reliable knowledge, and we invest it with cultural authority, free of the cynicism with which we view other formal discourses such as politics (see Hyland 2000).

2.4.2.1 ICT for Sustainability (In the Information Society)

ICT is a fundamental aspect of modern society. It has over the last few decades shaped the emergence of many labels of new kinds of society, such as information society, network society, knowledge society, and postindustrial society—these are seen as the successor to industrial society. These visions of a new era have materialized as a result of the pervasive and transformational effects of ICT. ICT offers a new vision for European information society (e.g., ISTAG 2006), which promises to transform the way it functions. There is no universally accepted notion of what can be termed information society. It can be described as a society where new ICT is used to create, disseminate, use, apply, and manipulate information as a significant economic, political, social, and cultural activity. Here, technological innovation is a key element to get closer to information as an agglutinative aspect. According to Bell (1974), a postindustrial society is where information is of a central preoccupation and the prime source of innovation and social dynamism and power. He predicted that advanced societies would, by the end of the twentieth century, reach the postindustrial stage, demonstrated by the growing importance and use of ICT. Theories of industrial society argue that information will increase in importance compared to industry (Sztompka 2002). The increase in performance of computers and the development of communication technologies is a mega-trend that will alter societies on a worldwide scale (Sztompka 2002).

Much of the discourse about information society constructs ICT as being a powerful enabler for societal transformation. Discursive constructions pertaining to ICT for societal transformation are abundant and powerful in all kinds of academic and scientific publications and writings. ICT is unleashing far-reaching societal change and is necessary "for bringing more advanced solutions for societal problems" (ISTAG 2006). Major opportunities exist for new ICT to address environmental pressures and, in relation to improving Europe's economy, support new approaches to sustainable development (ISTAG 2003). GeSI (2008, p. 7) states: "ICT provides the solutions that enable us to 'see' our energy and emissions in real time [so]…to make them more efficient." According to Griffiths (2008), there are various uses of ICT that could substantially improve energy efficiency and mitigate global GHG emissions, among which include smart grid, smart industry, smart buildings, dematerialization, integrated renewable solutions, and city planning. Furthermore, it is widely accepted that ICT could decouple the economic growth from environmental degradation because of its potential to, besides improving productivity through sophisticated processes, generate value-added in the form of manipulating information rather than energy. In all, the underlying belief of the discourse of information society is that a total social transformation is envisioned or predicted and that this transformation is a positive and progressive movement. In relation to sustainable development, the existing evidence lends itself to the argument that the ubiquity presence and massive use of ICT make it a salient factor for advancing sustainability.

As ICT has become more sophisticated and deeply embedded into the very fabric of the contemporary city, it has provided many new opportunities to make sustainable urban development work by drastically transforming the way the city functions and can be managed, planned, and developed in terms of different dimensions of sustainability as well as efficiency. The new digital transition fueled by ICT of pervasive computing and its constitutive nature, on which many cities across the globe are increasingly engaging, is projected to bring about further transformational effects. It has been widely acknowledged that ICT innovations embody a morphing power in that they alter how cities evolve as well as reshape and create new urban realities. Viewing ICT as a constitutive and integrative technology represents a widening and deepening of UbiComp-, AmI-, and the IoT-, and SenComp-type approaches at the level of urban applications. These disruptive digital technologies and their amalgamation are postulated to transform the role of ICT in the city and ultimately the way citizens live. This involves capturing further and invigorating the application demand for the urban sustainability solutions that emerging and future ICT can offer. In particular, the constitutive nature of ICT of pervasive computing amounts to a paradigmatic change in the way the city functions, whether be it smart, sustainable, or smart sustainable. The convergence of emerging ICT will shape future cities in fundamental—and yet unexpected—ways (e.g., Shepard 2011; Batty et al. 2012). This involves how they can be monitored, analyzed, probed, assessed, and planned to improve their contribution to the goals of sustainable development by relying on big data analytics and context-aware computing (Bibri and Krogstie 2017b). Not only is ICT seen as a critical enabler but also as a powerful transformative driver for achieving such goals. Indeed, without ICT, the drive to improve urban systems: physical structures and spatial organizations, urban infrastructures and facilities, urban administration and governance, and ecosystem and human services, may not reach its full potential. Reaching full potential in this respect signifies new and fertile opportunities for improving urban sustainability, urban efficiency, and the quality of urban life, which ICT of pervasive computing is well placed to instigate, provide, and sustain. Indeed, a number of smart technologies are being developed and applied to diverse urban systems and related activities and processes to conserve resources, lower pollution levels, reduce GHG emissions, streamline processes, and enhance living standards, as well as being employed to investigate and evaluate the processes of their own application, implementation, and impact on the city. The research and social practice within the area of new ICT for sustainability has a key task to fill as to urban planning and development (e.g., Rivera et al. 2015). In other words, cities entail human environments where smart solutions in line with the goals of sustainable development can be discovered, created, employed, assessed, and improved. In a nutshell, ICT can be leveraged in the advancement of sustainable development and hence in addressing the challenge of sustainability and urbanization in the context of smart sustainable cities of the future.

ICT of pervasive computing is expected to yield environmental gains and socioeconomic benefits in line with the vision of urban sustainability, owing to its technological superiority in terms of the novel applications, services, and products that provide advanced performance and value. Especially, it ushers in automation in nearly all urban domain and system. This implies that the range of applications that utilize UbiComp, AmI, the IoT, and SenComp in connection with the urban sustainability domain is potentially huge, and significant opportunities are said to exist for these technologies, separate or combined, in relation to modernizing the urban model particularly in terms of advancing sustainability. It is clear that ICT of pervasive computing provide novel solutions and sophisticated methods for addressing environmental and socioeconomic challenges pertaining to sustainability that are increasingly facing cities.

2.4.2.2 ICT Visions of Pervasive Computing: UbiComp, AmI, the IoT, and SenComp

ICT of pervasive computing for urban sustainability is a recent discourse that is emerging in ecologically and technologically advanced societies within the defining context of smart sustainable cities (Bibri and Krogstie 2016a). It entails the most prevalent visions of ICT of pervasive computing, which in turn depict socio-technical visions and thus discourses.

Defining Characteristics

Implying a slightly different focus, UbiComp, AmI, the IoT, and SenComp depict ICT visions of various forms of pervasive computing—i.e., an era when computer "technology recedes into the background of our lives" (Weiser 1991). Since 1991, Mark Weiser foresaw this technological development and labeled it "the computer for the twenty-first century." These ICT visions are characterized by a future loaded with interconnected, interacting, deciding, and acting—and thus smart—everyday objects and devices as augmented with miniature sensors and actuators, tiny microelectronic processors, and wireless communication capabilities, as well as by a whole range of the fascinating opportunities this future will bring that are created by the (extensive) incorporation of computer technology into the very fabric of the city and thus citizens' everyday lives. The vision of the future of technology—reflected in a variety of terms (e.g., invisible computing, calm computing, proactive computing, wearable computing, and Things that Think, in addition to UbiComp, AmI, the IoT, and SenComp)—is associated with far-reaching, long-term societal implications and thus urban effects.

The concept of AmI describes an era when ubiquitous computing, communication, and intelligent user interfaces will function in such an unobtrusive way and converge in such a seamless way as to rendering technology completely calm and wholly invisible, with each citizen enjoying an experience of interaction with the environment that anticipates and intelligently responds to their needs and desires. ISTAG (2003, p. 8), the European Union's Information Society Technologies Advisory Group, describes AmI as a vision where people will "be surrounded by intelligent interfaces supported by computing and networking technology that is embedded in everyday objects… AmI implies a seamless environment of computing, advanced networking technology and specific interfaces. This environment should be aware of the specific characteristics of human presence and personalities, adapt to the needs of users, be capable of responding intelligently to spoken or gestured indications of desire,…AmI should also be unobtrusive, often invisible: everywhere and yet in our consciousness—nowhere unless we need it." AmI has taken on many other definitions in the literature (see Bibri 2015a for an overview).

SenComp denotes the use of sensing devices to observe and monitor and computing devices to perceive (recognize and interpret) the physical environment and react to it. It is the idea that applications can be made more perceptive and responsive by becoming aware of and reacting to their surroundings. This also applies to several application areas of AmI as smart environment (e.g., Bibri 2015a; Bosse et al. 2007). But AmI goes beyond the physical context to include other types of context such as cognitive, emotional, social, behavioral, conversational, and spatiotemporal, to underscore the difference between AmI and SenComp. In view of that, AmI and SenComp have been used interchangeably in the urban domain: ambient and sentient cities (e.g., Crang and Graham 2007; Shepard 2011).

The concept of UbiComp means that computer technology will permeate everyday human environment, and function invisibly and unobtrusively in the background, and make everyday objects smart by enabling them to communicate with each other, interact with people and their objects, and explore their environment, thereby helping people to carry out their daily activities or cope with their tasks in more intuitive ways and whenever and wherever needed, to draw on Weiser (1991). It is alluded to as a "computing environment in which each person is continually interacting with hundreds of nearby wirelessly interconnected computer…essentially invisible to the user" (Weiser 1993, p. 75).

The concept of the IoT (e.g., Huang and Li 2010; Uckelmann et al. 2011) refers to a computationally augmented everyday environment where the physical world (everyday objects) and the informational world are integrated within the ever-growing Internet infrastructure via a wide range of active and smart data sensing devices, including RFID, NFC, GPS, infrared sensors, accelerometers, and laser scanners. Bibri (2015b, p. 33) defines the IoT as "the interconnection of uniquely identifiable embedded devices, physical and virtual objects, and smart objects [connected to humans, embedded in their environments, and spread along the trajectories they follow] using the Internet Protocol version 6 (IPv6) [the new addressing infrastructure of the Internet with an unlimited capacity], embedded systems, intelligent entities, and communication and sensing-actuation capabilities." The IoT as an intriguing construct that is evolving into more and more sophisticated network of (sensor) devices and physical objects is estimated to involve all kinds of everyday objects, including people, roads, railways, bridges, streets, buildings, water systems, electrical networks, vehicles, appliances, goods, machines, animals, plants, soil, and air. In short, the connectivity achieved by the IoT involves people, machines, tools, and places. The aim of using the IoT is to achieve different intelligent functions from conducting information exchange and communication, including learning about things, identifying things, tracking and tracing things, connecting with things, searching for things, monitoring things, controlling things, evaluating things, managing things, operating things, repairing things, and planning things.

Differences, Commonalities, and Overlaps

The four identified technologies of models of smart sustainable city have already been described in Sect. 2.3. Here, we focus on some differences and overlaps among these technologies. While the concepts of UbiComp, AmI, the IoT, and SenComp tend to resemble each other, not least as to the underlying core enabling technologies (pervasive sensing, computing, data processing, and networking systems and infrastructures), they do entail a slight difference in terms of focus and orientation as well as the nature and scope of the applications they offer. The concept of AmI is similar to UbiComp in the sense of intelligence being everywhere (e.g., Poslad 2009). AmI is seen as the direct extension of UbiComp, as it adds the feature of adaptiveness and responsiveness to the user's needs and behaviors (e.g., ISTAG 2003; Riva et al. 2003). Compared to UbiComp, AmI is concerned more with the use of the technology by people than the technology itself, i.e., AmI centers on users in their environment and is user-pull oriented whereas UbiComp focuses on next-generation computing and is technology-push oriented. As to the IoT compared to AmI, the focus in “the IoT is on the use of the existing Internet structures to link devices and objects, a technological feature that is not a prerequisite in AmI” (Bibri 2015b, p. 32). However, the IoT entails, like AmI, sensors and actuators, smart things, and wireless technologies. One implication of this is that the IoT applications can configure themselves in reaction to, or when exposed to, new environments, an intelligent behavior that can autonomously be triggered to cope with potentially unforeseen situations (Vongsingthong and Smanchat 2014). With embedded smart sensors, smart things can “process information, self-configure, self-maintain, self-repair, make independent decisions, or even play an active role in their own disposal” (Vermesan and Friess 2013). Objects are said to have AmI capabilities, when they interact with the environment and act autonomously. The slightly different focus implied by the concept of SenComp in relation to AmI lies in that it looks at the environment as the interface, and this environment could represent spatial scales or geographical locations. In this context, a common use of sensing and computing devices is to build and maintain a world model which allows various context-aware applications and environments to be constructed and operate intelligently in relation to diverse urban domains within neighborhoods, districts, or cities. Notwithstanding there are demarcation lines between UbiComp, AmI, the IoT, SenComp, and other related fields, “efforts emanating from all of these fields modulate urban life and their effects overlap and reinforce one another” (Böhlen and Frei 2009, p. 1).

UbiComp, AmI, the IoT, and SenComp as technological paradigms share the same core enabling technologies underlying ICT of the new wave of computing, namely sensing devices and networks, intelligent components where processing and modeling occur, actuators for the systems’ behavior or application actions in the physical and virtual world, and wireless communication networks that tie all these devices, systems, and applications together. The aim of the related platforms is to orchestrate and coordinate the various computational entities in the physical and virtual spaces into an open system that helps people cope with or carry out their daily activities within a wide variety of settings. However, there are basically various permutations of the core enabling technologies underlying UbiComp, AmI, the IoT, and SenComp, depending on the application domain and its complexity and scale. This implies that there exist a vast range of related architectures that essentially aim to provide the appropriate infrastructure for these technological landscapes (see, e.g., Bravo et al. 2006; Kyriazis et al. 2014; Perera et al. 2014; Shepard 2011). Lee et al. (2008) provide an example of the core enabling technologies underlying UbiComp in relation to the application domain of ubiquitous city. Applicable to all forms of pervasive computing is the idea that many heterogeneous computable components are spread across diverse networks which interconnect through middleware, cloud computing, or cloud middleware infrastructures as part of vast architectures enabling data collection and capture, data mining and machine learning, hybrid modeling and reasoning, intelligent decision support, service provisioning, and application actions. These technologies, tools, and techniques are in the context of this chapter associated with big data analytics and context-aware computing as a set of applications and the associated urban intelligence functions and simulation models, among other things.

ICT of Pervasive Computing as Enabler for Smart Sustainable Cities and Smarter Cities

The rationale behind selecting and thus defining the above notions is that the ICT visions they pertain to are more prevalent than those associated with their counterparts. This is manifested in the emergence and widespread of ubiquitous cities, ambient cities, sentient cities, and cities as an Internet-of-everything. Enabling different kinds of computationally augmented urban environments in these emerging cities and seeking to connect urbanites with each other and such environments, the technologies underlying UbiComp, AmI, the IoT, and SenComp will enable all kinds of smart applications, such as smart living and working, smart health care, smart education, smart safety, smart energy, smart climate, smart buildings, smart transport, smart mobility, smart accessibility, and smart planning and design. This smartness holds great potential to increase the contribution to urban sustainability in terms of its physical, environmental, economic, and social dimensions.

Smart sustainable cities typically rely on the fulfillment of the prevalent ICT visions of the new wave of computing (Bibri and Krogstie 2016a, 2017a), a merger of UbiComp, AmI, the IoT, and SenComp. In other words, such cities are associated with the core characteristic features of the prevalent ICT visions in the sense that everyday objects communicate with each other in various ways and collaborate across heterogeneous and distributed environments to provide information and services to diverse urban entities. For what such ICT visions entail, the prospect of smart sustainable cities is becoming the new reality with the massive proliferation of the core enabling technologies underlying ICT of the new wave of computing. Particularly in ecologically and technologically advanced nations, this computerized urban era is pervading many cities and rapidly evolving, characterized mainly by the use of smart and data-centric applications across urban systems and domains. Indeed, visions of future advances in computing and ICT bring with them wide-ranging common visions on how cities as social fabrics and forms for human settlements will evolve in the future (Bibri and Krogstie 2016a).

2.4.2.3 Sustainability

The notion of sustainability was born from the realization that the predominant paradigm of social, economic, and urban development was oblivious to both the risks of, and triggering, environmental crises as well as to the implications of, and worsening, social decays, causing ecological and social deprivation and imperiling future life. In other words, sustainability has grown out of an urgent need for real change—due to serious concerns that the model of societal development has been performing poorly in protecting the environment and improving the quality of people's lives. In particular, there is mounting evidence that economic development has caused ecological deprivation and unprecedented levels of GHG emissions. This is due to the instrumental rationality underlying the economic model. This specific form of rationality, the dominant mode of thinking and action in the industrial world, focuses on the most efficient means—the how of actions—to achieve a specific end, or on identifying problems and working directly, and often unreflectingly, toward developing their solutions, thereby lacking any consideration of limits, but not in itself reflecting on the value of that end (or evaluating the consequences of those actions). Further, the obliviousness to the environmental threats fueled by the instrumental rationality of the economic model has triggered innumerable complex environmental crises with catastrophic global effects on human health, well-being, stability, and safety. Predictably, it has been argued that it is only by altering the foundational theories and assumptions underlying economics and politics that sustainable development may come true, and eventually sustainability may be achieved. In fact, there is a need for the kind of rationality that goes beyond thinking instrumentally to embrace ways of seeing things form a more sensible, reflective, and holistic manner.

Grounded in a holistic thinking perspective, sustainability is based on the idea of consciously and incessantly going with the grain of nature and providing the conditions for deploying the frameworks necessary for its operationalization and its translation into practices in a more dynamically intelligent and innovative way in order to reach a sustainable society. Generating immediate worldwide attention upon the widespread dissemination of the concept of sustainable development in the late 1980s, followed by an unprecedented prevalence and wide adoption of related strategies, sustainability embodies a unique productive and constitutive force as a large-scale societal discourse. As such, it has widely been adopted to primarily guide and configure societal development (social system functioning, adaptation, growth, and evolution) in its prominent spheres, including science and innovation, technology, economy, urban development, policy, politics, ethics, institutionalization, and culture. The underlying premise is that it is grounded in an all-embracing understanding of the complex challenges and mounting problems facing society, which is necessary for making all-inclusive decisions and taking well-informed actions for its long-term benefit. Accordingly, sustainability as a form of holistic thinking grounded in systems view deals with wholes rather than parts. One way of thinking about this is in terms of a hierarchy of levels of socio-ecological organization and of the different emergent properties that are evident in the whole biosphere that are not evident at the level of economic and political systems as taken as separate units of analysis.

There is no canonical or definite definition of sustainability. It is a difficult concept to delineate given its contested, philosophical, normative, and multifaceted nature, in addition to the complexity of the socio-ecological system to which it is applied. Sustainability depicts a state in which society does not systematically undermine natural and social systems within the biosphere, i.e., a state in which the four "sustainability principles" are not violated (Robèrt et al. 1997). In more detail, in such a state the natural system is not subject to resource depletion and intensive consumption, hazardous substances, environmental degradation, and concomitant environmental risks, and, as of equal importance, the social system does not render people subject to conditions that inhibit their ability to satisfy their needs and aspirations. Undermining natural and social systems can occur through pollution, environmental degradation/ecological deprivation, health decrease, social instability, social injustice, and social hazard. Accordingly, sustainability starts by looking at the nature and behavior of the whole system (socio-ecological organization) that those participating have agreed to be worthy of study. This involves the three following criteria, according to Pearson and Ison (1997):

- Taking multiple partial views of "reality,"
- Placing conceptual boundaries around the whole, and
- Devising ways of representing the whole or systems of interest.

2.4.2.4 Environmental, Economic, and Social Dimensions of Sustainability

Much of the discourse around sustainability constructs or speaks about it as consisting of environmental, economic, and social dimensions, which should ideally be in balance in order to achieve the long-term goals of sustainability. In a sustainable society, the environment, the economy, and equity (3Es) should be enhanced on the long-term basis. In other words, sustainability articulates how society values the 3Es. Sustainability is often cast in terms of these 3Es, and their well-being should crucially be interrelated, not separated, due to their interdependence and equal importance.

Environmental sustainability means understanding and living within the carrying capacity of the ecosystem (material and systemic limits), i.e., sustaining its ability to meet current and future needs, by making decisions and taking actions that restore the quality of the environment and preserve its capability to support human life, or allow all people to live well, on the long-term basis. This entails ensuring that the interaction patterns between society and the natural environment occur in ways that perpetually conserve the latter. Toward this end, it is imperative to create systems and processes to monitor and manage biophysical constraints, thereby steering off from ignoring the links between ourselves and nature by finding ways to live mutually with it. In modern society, finding "ways of consciously *living with the grain of nature*" could possibly be the core idea of environmental concern; sustaining "human continuance through permanent living self-adjustment to systemic constraint thus grows naturally from the metaphorical root of environmental concern" (Foster 2001). To put it differently, the better sensemaking is to reshape ourselves to fit a finite planet than to attempt to reshape the planet to fit our infinite needs (Orr 2004).

The environment and the economy are seen by many economists as one interlinked system (Hamilton and Clemens 1999; Dasgupta 2007). Economic sustainability entails identifying and implementing various strategies for utilizing available resources optimally, or that make it conceivable to make the best use of their availability. The basic premise is to uphold the amount of consumption of these resources over the longer term in an efficient and responsible way, thereby shunning degrading capital stocks and providing long-term environmental benefits and economic gains.

Social sustainability involves equity, social justice, well-being, diversity, cultural enhancement, attention to the disadvantaged and disabled people, as well as agency and power in terms of who can decide and who benefits (e.g., from the use of advanced technologies and their novel applications and services). Maintaining these social conditions is assumed to support the ability of current and future generations to create healthy and livable communities, and thus to fulfill the social, cultural, and technological needs of people in equitable ways. Accordingly, social sustainability occurs when the systems, structures, relationships, and networks in the city actively support the capacity of all citizens to benefit from new technologies to create sustainable communities. To be socially sustainable, the combination of people and technology in modern, high-tech society should be configured so that the quality of life is adequate for all kinds of people in that society. A socially sustainable society is characterized by persisting over generations, adequate farsightedness and flexibility, and astuteness to bolster its social systems of support (Meadows et al. 1992). The underlying assumption is that living in inequitable and inadequate ways will degrade the quality of social fabric and trigger destructive disagreements and divergences. “A sustainable society implicitly connotes one that is based on a long-term vision in that it must…be a society of social justice because great disparities of…privilege will breed destructive disharmony” (Hossain 1995), conflict, insecurity, and vulnerability.

2.4.2.5 Sustainable Development

The word “sustainable” refers to something that can last, and “development” is commonly used to indicate growth primarily in quality, so not only in quantity. Sustainable development is a process of change and strategic approach to achieve the long-term goals of sustainability: a socio-ecological system in balance. It has emerged as a global response to the environmental crises triggered by anthropogenic activities and escalating social inequalities and injustices. The concept of sustainable development was introduced by the Brundtland Report in 1987, in which it denotes “development that meets the needs [and aspirations] of the present without compromising the ability of future generations to meet their own needs” (WCED 1987, p. 43). However, this classic definition has been misconstrued and misused and thus generated several critiques. As a result, the concept has become widely multifarious, highly contested, and oftentimes contradictory and oxymoronic (e.g., Hopwoodil et al. 2005; Jacobs 1999; Jöst 2002; Munda 1997; Murcott 1997; Redclift 1987, 2005). The lack or absence of a more universal definition of sustainable development has given rise to multiple interpretations and philosophical underpinnings, which has consequently triggered an explosion of environmental, social, and economic indicators. However, as one among many other alternative definitions in the literature, sustainable development is described by Bibri (2015b, p. 53) as "the planned and strategic development process of working toward a balance of economic, environmental, and social values and goals, i.e., a balance of the need for economic development and prosperity with environmental protection and integrity and social equity and justice. The premise is to conciliate the continuity of these—conflicting, competing, and sometimes contradictory—forces."

2.4.2.6 Urban Sustainability and Sustainable Urban Development

The concepts of sustainability and sustainable development have been applied to urban planning and design since the early 1990s (e.g., Wheeler and Beatly 2010), thereby the emergence of the notions of urban sustainability and sustainable urban development. Urban sustainability denotes a desired state in which the urban society strives for achieving a balance between environmental protection and integration, economic development and regeneration, and social equity and justice within cities as long-term goals through the strategic process of sustainable urban development as a desired trajectory. Thereby, it seeks to create healthy, livable, and prosperous human environments with minimal demand on resources (energy, material, etc.) and minimal impact on the environment (toxic waste, air and water pollution, hazardous chemicals, etc.). This overall goal entails fostering linkages between scientific and social research, technological innovation, institutionalized and organizational practices, and policy design and planning in relevance to urban sustainability. Urban sustainability tends to be cast in terms of four dimensions: the form, the environment, the economy, and equity, which should all—given their interdependence, synergy, and equal importance—be enhanced over the long run in a sustainable urban society. Accordingly, contemporary cities should retain a balance between physical, environmental, economic, and social concerns and goals. To achieve this long-term goal requires an urban development strategy that facilitates and contributes to the design, development, implementation, evaluation, and improvement of urban systems and other practical interventions within various urban domains that promote urban sustainability in terms of replenishing resources, lowering energy use, lessening pollution and waste levels, as well as improving social justice, stability, and safety. This is what sustainable urban development is about. This concept signifies, in other words, the development (and/or redevelopment) of cities in ways that provide livable and healthy human environments with enhanced quality of life and well-being in conjunction with decreased demand on resources and lessened environmental impacts, to reiterate, thereby steering clear of leaving a burden on the future generations due to potential environmental degradation or ecological deprivation. Richardson (1989, p. 14) defines sustainable urban development as "a process of change in the built environment which foster economic development while conserving resources and promoting the health of the individual, the community, and the ecosystem." In a nutshell, sustainable urban development seeks to achieve a balance between the development of and equity in the urban areas and the protection of the urban environment. However, conflicts among the goals of sustainable urban development to achieve the long-term goals of urban sustainability are challenging to deal with and daunting to overcome. This has indeed been, and continues to be, one of the toughest challenges facing urban planners and scholars as to decision-making and planning in the realm of sustainable cities, not to mention smart cities due to the multidimensional risks they pose to environmental sustainability. Despite sustainable urban development seeking to provide an enticing, holistic approach into evading the conflicts among its goals, these conflicts "cannot be shaken off so easily," as they "go to the historic core of planning and are a leitmotif in the contemporary battles in our cities," rather than being "merely conceptual, among the abstract notions of ecological, economic, and political logic" (Campbell 1996, p. 296). Even though these goals coexist uneasily in contemporary cities, sustainable urban development as a long-range objective for achieving the aim of urban sustainability is worthy for urban planners, as they need a strategic process to achieve the status of sustainable cities, to increase the contribution of smart cities to sustainability, and to spur the development of smart sustainable cities. As expressed by Campbell (1996, p. 9), planners will in the upcoming years "confront deep-seated conflicts among economic, social, and environmental interests that cannot be wished away through admittedly appealing images of a community in harmony with nature. Nevertheless, one can diffuse the conflict, and find ways to avert its more destructive fall-out." To put it differently, sustainable urban development advocates can—and ought to—seek ways to make the most of all three value sets at once. This is in contrast to keeping on playing them off against one another. With that in mind, the synergistic and substantive effects of sustainable development on forms of urban management, planning, and development require cooperative effort, collaborative work, and concerted action from diverse urban stakeholders in order to take a holistic view of the complex challenges and pressing issues facing contemporary cities.

In the context of this chapter, the focus is on the smart dimension of urban sustainability and sustainable urban development. In this regard, urban sustainability consists of four dimensions: physical, environmental, economic, and social, which should be enhanced in terms of goals and be in balance in terms of concerns over the long run—with support of advanced ICT—to achieve the smart form of sustainability. This can occur through strategic smart sustainable urban development—i.e., a process of change in the built environment driven by ICT and other technological innovations that seeks to promote sustainable built form, environmental integration, economic regeneration, and social equity as a set of interrelated goals. In other words, to foster economic development while conserving resources and promoting the health of the ecosystem and its users requires innovative solutions and sophisticated approaches resulting from unlocking the untapped potential and transformational effects of ICT in terms of its disruptive and synergetic power given its enabling, integrative, and constitutive nature. Such process ought to be based on amalgamating the research agenda of urban computing innovation and urban ICT development with the agenda of sustainable urban planning and design, thereby justifying ICT investment and its orientation by environmental concerns and socioeconomic needs within contemporary human settlements. This endeavor should in turn be supported by pertinent institutional structures and practices and policy frameworks and measures.

2.4.3 On the Discursive and Social Dimensions of Smart Sustainable Cities

2.4.3.1 Discursive Genesis

The debate focusing on the untapped potential of ICT of pervasive computing for catalyzing and boosting sustainable development toward achieving the long-term goals of sustainability relates to the academic discourse of ICT for sustainability. This discourse has given rise to other discourses, such as ICT for urban sustainability (e.g., van den Berg and van Winden 2000; Bibri 2013) and ICT for environmental sustainability (e.g., Fuchs 2005). The discourse of ICT of pervasive computing for urban sustainability (Bibri and Krogstie 2016a) has gained popularity after the prevalent ICT visions of pervasive computing (namely, UbiComp, AmI, the IoT, and SenComp) have become deployable and achievable computing paradigms. Moreover, the increasing amalgamation and use of these computing paradigms in terms of the underlying core enabling technologies in relation to a number of urban domains in the context of sustainability has contributed to the materialization of the discourse of smart sustainable cities. Smart sustainable cities represent one of the key defining contexts of ICT of pervasive computing for urban sustainability (Bibri and Krogstie 2016a). On this note, Phillips and Jørgensen (2002) point out that concrete language use can change the social and cultural world by combining elements from different discourses. However, all the above discourses metonymically represent the discourse of sustainable information society, a meta-discourse which regulates the techno-urban discourse of smart sustainable cities. Sustainable information society "is conceived as a society in which new… ICT…and knowledge are used in order to advance a good-life for all individuals of current and future generations. This idea is conceived in a multidimensional way, identifying ecological, technological, economic, political, and cultural aspects and problems" (Fuchs 2005, p. 219).

Advances in science and technology (predominantly computing and ICT) inevitably bring with them wide-ranging common discourses and visions on how cities as forms for human settlements and complex systems will evolve as well as on the immense opportunities to benefit from and the potential risks to face. The techno-urban discourse of smart sustainable cities expresses a vision of city with healthy, livable, and prosperous human environments as well as minimal demand on resources and minimal environment impacts, all enabled by advanced computing and ICT as a form of science and technology. In this vision, ICT solutions hold great potential to tackle and solve environmental and socioeconomic problems, or to address the challenge of sustainability. And in this discourse, there is a construction of “the city” as a relevant techno-urban category and as something desirable and often equal with the objects, yet not the scope, of city governments. Further, similar discourses pertaining to other spheres of society have been common with the advent of technological innovations and breakthroughs. They have made claims and promises about different kinds of social transformations on the basis of the innovations and breakthroughs enabled by computing and ICT over the last few decades. All such discourses can be stimulating and compelling when new and strongly disruptive technologies (e.g., UbiComp, the IoT, AmI, SenComp) are emerging and pervading into society. Unlike other techno-urban discourses (e.g., smart cities), which have failed to deliver what they claim or live up to their expectations due to the underlying technologically deterministic view, smart sustainable cities already place a strong focus on urban dynamics around the new features enabled by ICT of the new wave of computing and their potential adoption for advancing sustainability rather than solely emphasizing these new features. The rationale behind this argument is that smart sustainable cities are taken to mean or assumed to be ecologically sustainable based on established theoretical foundations of sustainable urban planning, and ICT of the new wave of computing is seen more as a constitutive and integrative technology whose transformational effects can be unlocked and leveraged in the advancement of urban sustainability. As concluded by Kramers et al. (2014), there is a weak connection between smart cities and environmental sustainability, as these cities have little to do with environmental solutions or concerns, and are intended to promote urban image and attractiveness and thus attract investment, businesses, and citizens; hence, it is suggested to use the concept of smart sustainable cities as a way of linking smart initiatives with environmental sustainability. There is tremendous untapped potential for harnessing the creative and disruptive power of ICT of the new wave of computing to transform the way sustainable cities function and ultimately the way citizens improve their sustainable living. With the above reasoning in mind, the techno-urban discourse of smart sustainable cities tend to reflect realistic assumptions about the evolution of sustainable urban practices, enabled by the applications and extension of complexity sciences and data science, which ICT of the new wave of computing is founded on, as well as about the complexity and scalability of the frameworks proposed for advancing urban sustainability. In this sense, the intention is not to mimic and enhance existing urban functions and practices, but rather let the disruptive nature of technological innovations and breakthroughs dictate. It may well be more beneficial to search for the emergence of new sustainable urban practices around ICT of the new wave of computing and its wider use in the urban domain. In this respect, new sustainable urban practices can develop around advanced ICT (e.g., big data analytics), and it can further be adapted and integrated into such practices, thereby enhancing its use in a way that fits into a wider strategy that makes it more meaningful and strategically focused.

Referring to smart sustainable cities as a discourse is predicated on the assumption that it is a techno-urban phenomenon for which there is no clear, definite, and widely acknowledged definition, in addition to the fact that urban scholars and practitioners are still writing about it. And in doing so, they are engaging in debates about smart forms of sustainable urban development. The discussions resulting in or forming this new discourse produce and make real the new urban reality of smart sustainable cities and thus develop jointly constructed understandings, thus the social construction of the related techno-urban category (see Bibri and Krogstie 2016a for further details). Indeed, the techno-urban discourse of smart sustainable cities is becoming powerful and established (e.g., Al-Nasrawi et al. 2015; Bibri and Krogstie 2016a; Höjer and Wangel 2015; Kramers et al. 2014, 2016; Rivera et al. 2015), as contemporary urban scholars and practitioners relate to it in a structured way in many contexts of their practices—socially anchored and institutionalized actions.

2.4.3.2 Discursive Hegemony

The discourse of ICT of the new wave of computing for urban sustainability and the discourse of smart sustainable cities depart from and build on the same assumptions and claims. Put differently, the latter is the current defining context for the smart and innovative solutions being suggested or offered by the former, which implies that other potential urban development strategies are likely to emerge in the future. At present, promoting and achieving urban sustainability with support of ICT of the new wave of computing occurs within and through smart sustainable cities, which typically rely on a combination of various forms of pervasive computing. With that in mind, we focus the discussion herein only on the discourse of smart sustainable cities. This discourse becoming more powerful and established as a scholarly discourse is demonstrated by the contemporary scholars and practitioners from many disciplines and professional fields, respectively, relate to it in a structured way in many contexts of smart urban planning and development practices. In a nutshell, it is a "hegemonic discourse" (see, e.g., Sum 2004; Hajer 1995), not least within ecologically and technologically advanced societies (Bibri and Krogstie 2016a). The discursive hegemony of smartness over the current form of sustainable urban development is manifested in the discourse of smart sustainable cities becoming so embedded in the information society that appears of uttering nonsense to ask about its assumptions. The ICT of the new wave of computing orientation of the development of sustainable city has gained dominance in that society under that discourse, which as a separate discursive field represents a cluster of discourses that revolve around the relationship between computing, ICT, sustainable development, sustainability, and urban planning that is given meaning, form, and ultimately applied in ecologically and technologically advanced societies. This implies that this discourse has gained legitimacy as an academic discourse and thus urban planning practice—i.e., pursued through diverse development strategies and projects pertaining to smart sustainable cities, supported by research and innovation endeavors. In particular, the growing academic interest in this discourse is such that it has become part of mainstream debate in sustainable urban planning and sustainable city-related disciplines. This is because of the (perceived) potential of innovative ICT to catalyze and boost sustainable urban development processes and, thus, to advance urban sustainability. In addition, this discourse and its translation into hegemonic techno-urban projects and strategies and their ongoing institutionalization in urban planning and development structures and practices postulate that, to reiterate, future visions of noteworthy advances in science and technology (computing and ICT) bring with them wide-ranging visions of the future on how cities will evolve and the opportunities such future will bring as to, e.g., sustainability, efficiency, and the quality of life. The importance of techno-urban visions of the future which materialize subsequent to new scientific innovation and its technological applications lies in that such visions "have the power not only to catch peoples' minds and imaginations, but also to inspire them into a quest for new possibilities and untapped opportunities and to challenge them to think outside common mindsets" (Bibri 2015b, p. 3). This is of relevance as to the innovative ways that are mostly needed to address the challenge of urban sustainability and rapid urbanization (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017b; Bifulco et al. 2016; Townsend 2013). In relation to this, like other (academic) urban discourses, the discourse of smart sustainable cities, which is constructed in the light of new conceptions about the scientific, technological, environmental, economic, institutional, social, and cultural changes over the past decade—"contains an all-embracing understanding of the problems cities are facing and is also the defining context for suggested [ICT] solutions" (Jessop 1998, p. 78) as future possibilities for the challenges and problems of urban sustainability and rapid urbanization.

2.4.3.3 Discursive-Material Dialectics, Construal, and Construction

With being a hegemonic semantic order, smart sustainable cities as a techno-urban vision have been construed and constructed (see, e.g., Jessop 2004; Fairclough 2005). That is to say, they have resonated with material mechanisms and practices. Constituting techno-urban objects and their related subjects with specific material and ideal interests (discursive constructions), smart sustainable cities have a pivotal role alongside material mechanisms and practices in reproducing and/or transforming urban domination (see Sum 2006). Smart sustainable cities as representations have been discursively construed in different spatial contexts (cities within ecologically and technologically advanced nations) and reproduced materially through institutional and organizational apparatuses and their techniques, actors, and practices (see Jessop 2004). This material reproduction entails the translation of the underlying techno-urban vision into hegemonic techno-urban strategies, projects, and initiatives as well as their institutionalization in city structures and urban practices. As regards to the construal of smart sustainable cities, Jessop (2004, p. 164) asserts that the relative success of discursive construals, which "can be durably constructed materially," "depends on how… [it] and any attempts at construction correspond to the properties of the materials…used to construct social reality." This supports the argument about the discursive-material dialectics and the importance of discursivity and materiality to an adequate account of the reconstruction of sustainable urban transformation. Specifically, focusing on how urban politics in relation to smart sustainable cities is done in a dialectic interplay between "*discursive selectivity* (discursive chains, identities, and performance) and *material selectivity* (the privileging of certain sites of discourse and strategies of strategic actors and their mode of calculation about their "objective interests," and the recursive selection of these strategies)" (Sum 2006, p. 8) in different spatial contexts is crucial to understand why the new discourse of smart sustainable cities has been translated into concrete projects and strategies and, thus, policy orientation has been legitimated with references to it. In all, there is a mutual dependence between semiosis and the material world, a dialectic interplay in which smart sustainable cities is constructed as an urban reality from an ontological standpoint. Semiosis refers to "the intersubjective production of meaning" and can be viewed as an umbrella concept for discourse and language (Jessop 2004, p. 161).

The dialectic of discursivity and materiality is in turn crucial to the social construction of smart sustainable cities. This involves developing, institutionalizing, and conventionalizing this techno-urban phenomenon by the information society (specifically ecologically and technologically advanced societies) through social constructs or cultural frames. These constructs or frames represent models of the urban world that are created, shared, and reified through language in the form of scientific documents and academic publications. Social constructionism posits that people rationalize their experiences through models and language (Leeds-Hurwitz 2009), concrete language use. Further, social constructs or cultural frames are produced by and depend on contingent aspects of people as social selves through social practices which form objects that an array of previous and current academic discourses on cities and urban development talk about. Accordingly, the constitution and reconstitution of urban life occurs through text production and consumption processes. This is predicated on the assumption that social and cultural change (production and reproduction) occurs through discursive practices. In light of this, recent years have witnessed a proliferation of scholarly writings on the growing role of ICT of the new wave of computing in advancing urban sustainability (e.g., Bibri and Krogstie 2016a), a form of semiosis which has generated the current discursive constructions of ICT of the new wave of computing for urban sustainability. The related magnitude and diversity of academic research have in turn given rise to smart sustainable cities as a holistic approach into urban development. This body of work continues to flourish and is consequently instigating drastic urban transformations in terms of the way the city functions and can be developed and planned. This is being fueled by the academic debates on sustainability science (e.g., Clark and Dickson 2003; Clark 2007) and its technology orientation in relation to evaluating and mitigating the unintended consequences of anthropogenic activities "on planetary systems and on societies across the globe and into the future" (Kieffer et al. 2003), in general, and its connection with ICT of the new wave of computing in the context of urban planning and development (e.g., Bibri and Krogstie 2017b), in particular. Sustaining the momentum is also explained by the resonance of this new intellectual trend with the practices of local city governments, landscape architects, urban planners, infrastructure companies, research institutions, sustainable development institutes, policymakers, and ICT industry consortia. These corroborating aspects pertain to smart sustainable urban development studies, projects, initiatives, and policies taking place within ecologically and technologically advanced societies across the globe.

2.4.3.4 The Interplay Between Cultural Frames and Discourses

There is a dialectic relationship between discourses and cultural frames in that discourses are shaped by and also shape cultural frames. In more detail, cultural frames exist within and through the coexisting discourses circulating in society, and are in these discourses reconstructed, transformed, and challenged, as well as shape how these discourses evolve new forms, as they both change through social practices. Advanced by Fisher (1997, p. 5), the concept of cultural frames refers to "socio-culturally and cognitively generated patterns which help people to understand their world by shaping other forms of deep structural discourse." Accordingly, smart sustainable cities are the product of a socioculturally conditioned framework in terms of how the associated urban practices have evolved through sociopolitical institutions as well as social processes which create and maintain knowledge pertaining to urban planning and development (e.g., establishing an intellectual connection between ICT of the new wave of computing, sustainability, sustainable development, and urban planning). It is in social processes that the ways in which we understand the world are produced and perpetuated (e.g., Burr 1995; Gergen 1985). Social processes represent forms of social interaction in which common truths, values, assumptions, claims, and legitimacies are constructed. Further, smart sustainable cities have in large part been brought to existence through strategic societal actors and their cultural frames that are attuned to the values of, and conventionalized by, ecologically and technologically advanced societies in relation to scientific innovation and technological development and their role in bringing about social transformations (e.g., sustainable urban change). Inextricably linked to, if not equated with, social constructs, which form the basis for shared assumptions about reality, cultural frames, which constitute shared forms of understanding the world, pertain to the meaning placed on the objects and their associated subjects with different material interests pertaining to smart sustainable cities that are constituted discursively by those societies and adopted by their constituents with respect to how they view or deal with the objects and subjects in question. Important to note is that social constructs or cultural frames may or may not represent a reality shared by those outside ecologically and technologically advanced societies. Yet, they have significant and often unrealized effect on people's perceptions of reality. They are, drawing on Moscovici (1984), "prescriptive in the sense that they represent a force, a combination of structures and traditions, which shapes the way people think and what they ought to think" (Bibri 2015b, p. 64). Regarding an example of cultural frames relating to ICT in the information society, ISTAG (2006, p. ii) states, “ICT does not just enable us to *do* new things; it *shapes* how we do them. It transforms, enriches and becomes an integral part of almost everything we do. …ICT becomes more deeply embedded into the fabric of…society… These constitutive effects amount to a paradigm shift in how our…society functions.” ICT research plays a key role in unlocking the transformational effects of ICT for societal sustainability (ISTAG 2006). ISTAG (2003, p. 8) adds in relation to AmI as a key strand of ICT of the new wave of computing, “we should not underplay the radical social transformations that are likely to result from the implementation of the AmI vision.” Therefore, the cultural frames linked to the role of ICT of the new wave of computing in societal (urban) development have shaped the structural discourse of smart sustainable cities as an instance of sustainable urban development. Indeed, smart sustainable cities typically rely on the fulfillment of the prevalent ICT visions of the new wave of computing, to reiterate. However, a key argument to underscore is that alternative discursive constructions could have been made had advanced societies chosen so. This implies that such discursive constructions will be formulated and thus new discourses on cities will be shaped in light of advanced conceptions about the societal changes yet to come. Fundamentally, discursive positions and constructions become recurrent and start sedimenting over time, respectively, as new alternative views and changes to arguments emerge and the established discursive positions and constructions get questioned and challenged. This occurs as people act upon discovered knowledge over and over and in doing so, transform discourses via social practice and social interaction.

The techno-urban discourse of smart sustainable cities is not shaped solely by the prevalent cultural frames, but also by recent cultural changes associated with advances in sustainability science and innovations in ICT. In fact, such changes have significantly affected the common cultural frames surrounding sustainable cities and smart cities, which have in turn given rise to a holistic approach into sustainable urban development as a deep structural discourse. In this regard, challenges have come from the macro level through cultural shifts relating to the increasing incorporation of environmental and socioeconomic concerns into regulatory incentives and policy frameworks as well as into norms and behavioral patterns in urban development. Adding to this is the growing societal realization that cities have become more complex through the very technologies being used to understand, analyze, and plan them in terms of their contribution to sustainability, thereby the need for the integration of complexity science and data science in their understanding, which the application of ICT of the new wave of computing is founded on (see, e.g., Batty et al. 2012; Bibri and Krogstie 2017a). Drawing on Smith (2003), drastic shifts to smart sustainable systems entail concomitantly drastic changes to the socio-technical landscape (including politics, policy, institutions, and social values), which involves such trends as increased sustainability awareness, climate change policy, and shifts to smart and smarter cities. In all, smart sustainable cities as a techno-urban innovation entail parallel social and cultural shifts as well as political actions. Hence, it is of high relevance to recognize the interplay between smart sustainable cities and other macro scales and the links to urban politics and processes of regulation (e.g., environment, technology, and innovation policy in support of cities).

ICT of the new wave of computing for urban sustainability is seen as a social process in which computational and technical dimensions are only partial factors. This relates to, among other approaches, the Social Shaping of Technology (SST), an umbrella term for socio-constructivist approaches to technological visions, which analyzes the politicization of technological culture (e.g., Boczkowski 2004) and focuses on power patterns, structures, and relations that are inscribed in technological development. This implies that the political dimension is implicated in ICT of the new wave of computing for urban sustainability as a social process in the sense of the exercise of the political power and the management of political dissension alongside the scientific discourse in the defining setting of smart sustainable cities. This dimension pertains to the social strand of urban sustainability, to be precise. Central to SST in terms of the link between technology and society is the premise that the trajectory of technological innovation entails inherent choices, so too the design of technological artifacts and systems (e.g., Robin and Edge 1996). This trajectory, i.e., the course of the development of ICT of the new wave of computing for urban sustainability, is sought to be created, shaped, and influenced by the interactions among social and historic actors and their actions through an array of boundary objects (methods, tools, procedures, rules, norms, etc.) that enable and facilitate interaction and action between different domains of shared beliefs, including political thinking and social norms, about what is of prominence as substantiated by the discursive and material practices pertaining to smart sustainable cities. One implication of this is that alternative choices of technological innovation—and hence alternative designs of ICT of the new wave of computing for urban sustainability—could be made and hence could have different implications for smart sustainable cities and for their urbanites. Put differently, there are always other discursive paths available to pursue that can potentially lead to different material consequences in terms of socioculturally sustainable urban development subsequent to alternative choices and outcomes of technological innovation. SST focuses on the influence of the sociopolitical context of development, which shapes the choices and outcomes of technological innovation. This in turn affects the trajectory of techno-urban transformations resulting from this innovation (e.g., smart sustainable cities).

2.4.3.5 Social and Cultural Contexts

The foreground of the normative facet of smart sustainable cities goes with the grain of the discourse of smart sustainable development that plays a key role in the debate on such cities. In the urban context, the word "sustainable" as a socially constructed concept essentially concerns normative values, and hence implies a certain desired state of the city and thus the trajectory of its development. In a similar vein, the word "smart" has been seen as an intended outcome (e.g., Bibri and Krogstie 2016a) rather than as an instrumental concept. As such, it becomes just as normative as sustainable (e.g., Höjer and Wangel 2015). Arguably, this conclusion cannot be that simple, as what is smart is not necessarily sustainable.

Regardless, while there is an ongoing debate about whether theories can travel, which has resulted from the long tradition of urban politics studies (e.g., Judge et al. 1995), it is widely acknowledged that many of the urban theories apply to different contexts (e.g., American cities versus European cities) (Clarke 2006; John 2001). Accordingly, it is possible to discuss a universal form of urban sustainability as underpinned by the existing large body of research in the field, but it may not be the case when speaking about the smartness of urban sustainability given the paucity of research (e.g., a large number of accumulative and illustrative case studies) in this regard. As the discourse on the necessity of cities being smart sustainable is present in many ecologically and technologically advanced societies, we still need to reformulate what city politics and policy is about in different contexts. On this note, urban sustainability performance is not necessarily linked to or indicated by the number of smart initiatives launched in a given urban project, but such initiatives could reflect certain efforts made to improve some aspects of sustainability (see Neirotti et al. 2014). In their recent study, Al-Nasrawi et al. (2015) concluded with reference to smart sustainable cities that what smartness means in different urban contexts is a subject of an ongoing theoretical debate, and there is a gap in knowledge as to the holistic assessment of smartness in such cities. In relation to this argument, it is worth pointing out that the social context (factors, elements, and actors) is essentially the crucible for ICT development and innovation in terms of which kind of new technologies and their novel applications are more embedded—and hence more promoted and disseminated—than others in different local social and cultural contexts. This relates to social studies of technology (e.g., Geels 2005; Smith 2003), an approach which analyzes the topic of technological change and innovation and centers on specific technologies which are embedded in local social and cultural contexts. This approach highlights that the established socio-technical regimes can induce and support the transformation of socio-technical constellations (e.g., industry associations, research communities, policy networks, and advocacy/special interest groups) toward certain goals at the macro level (e.g., Bibri 2015b), e.g., advancing urban sustainability by focusing on energy efficiency or green technology. Socio-technical regimes refer to "interconnected systems of artifacts, institutions, rules, and norms" (Berkhout et al. 2003, p. 3) that provide stability to the dominant socio-technical systems associated with technological innovation systems. To put it differently, sustainable technological niches, e.g., big data analytics and context-aware computing for urban sustainability (Bibri and Krogstie 2017a, b), are based on the socio-technical landscapes (e.g., nations and regions) within which they arise and operate, and that are supportive of innovation activities. Providing the space for radical innovation and experimentation, technological niches are defined as "loosely defined sets of formal and informal rules for new technological practice, explored in societal experiments and protected by a relative small network of industries, users, researchers, policy makers and other involved actors" (Raven 2005, p. 48).

In relation to urban sustainability, however, the intellectual challenge facing the city pertains to the idea that new technologies are not only developed to enable us to do and create new things and shape how we develop and revolutionize them, but also to study the processes of their own implementation and implication on the city—e.g., smart sustainable cities as a set of smart applications and systems and their actual role in advancing sustainability. This is predicated on the assumption that “technology and society are shaped at the same time in a mutual process,” i.e., the former develops dependently of the latter, thereby affecting each other and evolving in that process (Bibri 2015b). As succinctly put by McLuhan (1964), we shape technology and thereafter it shapes us. This is the kind of challenge that needs to be resolved in the development of smart sustainable cities that will improve their contribution to sustainability and thus enhance the quality of life of their citizens. ICT of the new wave of computing is expected to unleash the kind of sciences (computer science, systems science, data science, complexity sciences, etc.) that can be mobilized to instigate and sustain profound changes.

In all, ICT represents social constructions and thus its uses are inherently social and cultural (e.g., Bibri 2015b; Bijker et al. 1987) but also local. One implication of this is that there will be many ways of applying new technologies to address the challenge of urban sustainability and hence a diversity of smart sustainable urban projects and strategies as to the future of urban development. In view of that, there will be varied propositions about what makes a city, or how to make urban living, smart sustainable. It is crucial that ICT of the new wave of computing for urban sustainability (Bibri and Krogstie 2016a) takes into account the social and cultural context where ICT is embedded and its evolution is determined. This is critically important in order to mitigate any uncertainty and risk with respect to ICT development and innovation in the direction toward advancing urban sustainability in its own context.

2.4.3.6 Main Categories of Discourse About Smart Sustainable Urban Development

There are various categories of discourse about smart sustainable urban development to look at when pursuing questions pertaining to the design, development, and planning of smart sustainable cities of the future. In this context, discursive categories are aimed at providing insights into understanding the ways in which urban issues are socially constructed in terms of ICT and sustainability, i.e., the grounds underlying the claims that smart sustainable cities can make cities intelligently more sustainable. Based on an extensive interdisciplinary literature review on smart and sustainable cities (Bibri and Krogstie 2017a) and on a study on the social shaping dimensions of smart sustainable cities (Bibri and Krogstie 2016a), both particular aspects of the planning and design of smart sustainable cities and the way these are governed (including citizen science and civic participation and engagement) are part of the respective claims. On this note, at this stage of the development of smart sustainable cities, among the urban practice challenges include strategies for strengthening both the capabilities of city governments regarding ICT solutions as well as governance and planning models (Höjer and Wangel 2015). In particular, the organization of smart sustainable cities entails a reconsideration of which kinds of actors should be involved in city governance and planning (e.g., Anthopolous and Vakali 2012; Kramers et al. 2014; ITU 2014). At the core of this is how citizens are engaged in, and actively shape, decision-making processes. Batty et al. (2012) point out that the sustainability and quality of life issues will be dealt with using more effective models and simulations which involve an active engagement of a wider group of citizens in novel ways in the planning of their cities; in the information age, the city will be a determining factor for shaping policy analysis and planning, and the new technology will be a salient factor for planning forms of social organization. However, the issues around the design, planning, and governance of smart sustainable cities are subject to much debate among urban planners and designers as well as academics and policymakers. Drawing on recent studies on sustainable cities and smart cities as separate fields, there will be both convergences and divergences around the way in which these issues can be addressed. Yet, a convergence on a particular way of addressing the issues of the planning, design, and governance of smart sustainable cities would allow to identify what it means to be, or should be, a smart sustainable city. These issues can be pursued by looking at the more prevalent categories of discourse about smart sustainable urban development. These categories are described and elucidated below.

In terms of sustainability category, much of the discourse on sustainability speaks about it as entailing environmental, social, and economic dimensions, which ideally—in the fullest sense—should be in balance [created and maintained by sustainable development processes] for reaching the long-term goal of sustainability. Will that actually be the case in the future projects of smart sustainable cities, will one dimension dominate, or will those dimensions be loosely integrated? While this is for the future to tell, in sustainable cities (e.g., compact city and eco-city); social and environmental goals continue to play second fiddle while economic goals and priorities remain at the core of planning (e.g., Hofstad 2012). It seems that urban planners supported by urban scholars and urban policymakers will, for many years to come, face difficult decisions about how they set priorities as to, and where they stand on, protecting the environment, promoting economic development, and supporting social equity in the city. Hence, they will deal with deep-seated conflicts among these three essential goals, notwithstanding the optimistic view that new procedures are likely to emerge and develop that strengthen the influence of social and ecological goals over urban planning and development practices. Given the complexity and nature of the tension engendered among these three goals, sustainable development strategies cannot be adopted completely nor can sustainability be reached fully, but only partially and approximately, respectively. This may occur through a sustained period of reflective thinking about existing societal models, accepting unavoidable changes, and confronting and resolving rather unshakable conflicts. Indeed, the value of sustainability “lies in the long-term goals of a socio-ecological system [human society within the biosphere] in balance: society strives to sustain the ecological system along with the economic system and social system. Hence, as a goal set far enough into the future, sustainability allows us to determine how far away we are from it and to calculate whether (and how) we will reach it" (Bibri 2013, p. 8). Nonetheless, of importance to consider from the perspective of smart sustainable urban development is that for the diverse ICT solutions in smart sustainable cities to function requires a concerted action guided by a coordinating body with varied roles and competences in order to strategically assess the implications of ICT investments (see Höjer and Wangel 2015), as well as steering ICT innovations in ways that resonate with the process of sustainable urban development towards achieving the long-term goals of urban sustainability.

Regarding the category of smart sustainable city as a model, considering that the smart sustainable city is an emerging and quite ambitious model of urban development, it can be seen by the citizens and actors involved as something that can bring new opportunities for and new dimensions to the urban life. The smart sustainable city could epitomize a novel model of urban living to the world, something to break through to the mainstream and thus be replicated in different places across the globe.

As to the category of computing technology and urban design, the idea revolves around how smart sustainable city can advance and achieve sustainability. In considering ongoing smart sustainable city endeavors (e.g., Bibri and Krogstie 2017b; Kramers et al. 2014; Shahrokni et al. 2015), or existing smart and sustainable city projects, the potential associated with smart technological solutions involves different contexts of use. In terms of energy efficiency, as a common example, ICT can be integrated with renewable solutions by incorporating smart devices to enable the operation of renewable energy technologies. Also, ICT can be used to minimize the demand for energy resources or combining smart devices and passive solar design, one of the strategies through which sustainable urban forms can be achieved. In this regard, the interaction between urban structures and energy systems (using ICT tools) should take place on every spatial scale from the city, neighborhood, and district to the building (e.g., Jabareen 2006). Another use of ICT is associated with smart urban metabolism (e.g., Shahrokni et al. 2015). Other uses of smart technological solutions relate to transport efficiency and refinement, environmental management and monitoring, mobility and accessibility effectiveness, ecosystem service efficiency, quality of life enhancement, and so on. In all, there are a number of smart technological solutions that can be applied to urban activities and processes for improving sustainability, optimizing efficiency, and enhancing living standards. Such solutions depend on smart sustainable urban planning and on smart sustainable city projects that governments may implement in collaboration with ICT companies. In this regard, a competence of a coordinating body is needed to scrutinize offers (or turnkey solutions) from ICT companies, in addition to strategically assessing the overall outcomes of ICT investments in this direction (Höjer and Wangel 2015).

Concerning the category of urban sustainability by design and planning or governance and management, the focus is on the contribution of design versus governance to achieving urban sustainability in smart sustainable cities. In terms of design and planning, such cities may view sustainability as an outcome of endeavors undertaken during the design and planning phase and the extent to which smart ICT is emphasized as to its merger with sustainable urban forms: a city is a smart sustainable city because it has been designed and planned as such. As to governance and management, becoming a smart sustainable city may be contingent upon the way it will be governed and managed during and after the completion of smart sustainable urban projects: a city is a smart sustainable city because it is in its development and operation governed and managed as such.

As regards to the actors driving smart sustainable cities, the idea pertains to the actors that should be involved in the development of such cities, which is crucial for understanding their vision with regard to urban sustainability. Cities as social fabrics and backbones of civilization are the result of dynamic, intertwined, and multifaceted collaborations and networks of relations between and among people, communities, organizations, institutions, universities, governments, and other entities, with the aim of generating, disseminating, and implementing smart ideas and innovative solutions. As complex systems par excellence in light of the complex interdisciplinary knowledge and hence scientific and technological areas involved in their planning, smart sustainable cities entail a deep understanding of, and much of collective learning about, urban problems and systems. Therefore, they are developed through collaborative decisions and guided by a multitude of actions involving various players, i.e., multilevel, polycentric governance-based processes of planning and development. They have become even more complex through the very sophisticated technologies being used to understand, monitor, probe, assess, and plan them as urban systems. In all, numerous kinds of actors are involved in the development of smart sustainable cities as large-scale urban planning projects and comprehensive plans, including government, public sector, private sector, citizens, communities, civil society, academia, and expert advisors. And each actor has a role to play, which may depend on, or be completed by another actor, as to shaping, planning, developing, organizing, and assessing the smart sustainable city projects and initiatives.

2.5 Conclusions

The aim of this chapter was to systematize the very complex and dense scientific area of smart sustainable cities in terms of identifying, distilling, and structuring the core dimensions of a foundational framework for smart sustainable city development as a set of future practices. In doing so, it focused on a number of fundamental concepts and theories along with academic disciplines and discourses, with the aim of setting a framework that analytically relates city development, sustainability, and ICT, while emphasizing how and to what extent sustainability and ICT as theories have become influential in city development in modern society. This chapter primarily serves to facilitate collaboration between the different concepts and theories and academic disciplines and discourses underlying the interdisciplinary and transdisciplinary field of smart sustainable cities for the sheer purpose of generating the kind of interactional and unifiable knowledge necessary for a broader understanding of the topic of smart sustainable city development. This is a key contribution that supports the foundational ethos of the interdisciplinarity and transdisciplinarity that characterize the research area of smart sustainable cities. While the interdisciplinary approach is about pooling approaches from two or more disciplines and adjusting them so that they are better suited to the problem of smart sustainable city development, the transdisciplinary approach goes beyond pooling and adjusting disciplinary approaches to include their fusion for readily exploring the respective problem in its complexity. Therefore, espousing an interdisciplinary and transdisciplinary strategy in this scholarly endeavor makes it possible to flexibly respond to the topic under study in its intricacy and variety and thus uncover the best way of addressing it. This strategy is primarily aimed at contributing to an integral reflection over where the still-emerging field is coming from and where it is believed it should be headed, and how it should evolve in the next decades. With that in regard, the outcome of this work provides fertile insights into rethinking smart sustainable cities in terms of their development, with the capacity to create new methods for informing the city, sustainability, and ICT strands of urban planning and policy and to propose a holistic approach to conceiving of urban development.

The overall conceptual and theoretical framework, a collection of interrelated concepts and theories, is intended to support and guide this scholarly work, as well as to elucidate why the research problem being addressed exists and how it should be dealt with. In short, it represents an underlying basis for this scholarly work. It consists of the key relevant theories that can explain, predict, and understand the phenomenon of smart sustainable cities, as well as challenge, interrogate, reconfigure, and extend existing knowledge within the confines of critical bounding assumptions. These theories serve additionally to construct new knowledge by validating or evaluating explicitly stated assumptions. The relevance and importance of the conceptual and theoretical framework to this academic work lies in that it aids in eliminating potential preconceived notions pertaining to the topic of smart sustainable cities, which may otherwise result from biases or taken-for-granted assumptions, thereby avoiding the issue of not noticing things that might fit the implicit framework guiding this academic work, which deals with a rather complex and multifarious topic. The point is to make what can be an implicit framework more explicit by seeing the topic through theoretical lenses. The overall intention is to strengthen this academic endeavor by allowing the reader to reflectively and critically assess the assumptions explicitly enunciated, to connect to existing and dominating knowledge, and to transition from portraying the topic of smart sustainable cities as a new techno-urban phenomenon to uncovering and generalizing about its various dimensions—while identifying the limits to this generalization process. This is predicated on the premise that conceptual and theoretical frameworks may, in general, determine the specific assumptions that the research work involves with regard to analyzing and interpreting the scientific literature. All in all, the value of the conceptual and theoretical framework lies in fulfilling one primary purpose: to explain the nature, meaning, implications, and challenges pertaining to the emerging techno-urban phenomenon of smart sustainable cities. The commonly held view is that all phenomena are often experienced and explained from certain perspectives, but unexplored from somewhat other perspectives in the world in which we live, and that multi-perspectival approaches are accordingly useful for a broader understanding of multifaceted phenomena.

In addition, in the subject of smart sustainable city development, the underlying theories and academic disciplines and discourses and their integration are a foundation for action. In other words, the theoretical, disciplinary, and discursive dimensions of the foundational framework have strong implications for smart sustainable city development as a set of future practices. The synergic interaction between these dimensions produces a combined effect greater than the sum of their separate effects. This implies that this multidimensional framework has a supporting, underpinning, and shaping role in smart sustainable urban development. Of importance to underscore in this regard is that the theories of sustainability and ICT have become influential and prevalent in many aspects of urban life, whether in the built environment, urban systems, urban domains, urban services, or urban forms. This scholarly work focuses specifically on how sustainability can be integrated with ICT in their application to urban forms (design and planning of smart sustainable cities), and how this functions and is useful in an increasingly computerized and urbanized world. This theoretical integration is therefore of paramount importance as to how the subject of smart sustainable city development should be studied and applied. In other words, how sustainability and ICT theories are applied in the real world, how they work and how useful they are, constitute relevant subjects for this scholarly endeavor. There are many theories that are influential in how the subject of smart sustainable city development is studied and applied. There are some theories that may be strongly based on scientific evidence that would need expert knowledge to challenge, and others that are more philosophical and institutional and thus more open to general critical examination. What the implications of the integrated theories in this scholarly research are and whether such theories deliver what is claimed can be studied by examining actual case studies (city projects, programs, strategies, and future plans). This is being currently pursued as part of doctoral studies related to the topic of smart sustainable city development. In this way, theoretical issues and their effects are of primary focus in this scholarly work. This kind of research combines investigation and understanding of theory—a literature-based activity in conjunction with consultations with influential thinkers and experts in the field, to study the application and effects of theories. The Ph.D. study being undertaken thus involves an interesting and varied set of activities that are suitable for combining thinking with doing. Indeed, with its strong applied focus, it is not alienated or divorced from real life; rather, it is being carried out to inform the planning and design of smart sustainable cities as a holistic urban development strategy. In all, what underpins and motivates the pursuit of the applied theoretical approach is that the Ph.D. study is profoundly theoretically integrated yet under-researched, empirically underdeveloped, and inherently inductive. All in all, all institutionalized and socially anchored actions are grounded in some kinds of theories and academic disciplines and discourses.

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Chapter 3
Big Data Analytics and Context-Aware Computing: Core Enabling Technologies, Techniques, Processes, and Systems

Abstract Data sensing, information processing, and networking technologies are being fast embedded into the very fabric of the contemporary city to enable the use of innovative solutions to overcome the challenges of sustainability and urbanization. This has been boosted by the new digital transition in ICT. Driving such transition predominantly are big data analytics and context-aware computing and their increasing amalgamation within a number of urban domains, especially as their functionality involve more or less the same core enabling technologies, namely sensing devices, cloud computing infrastructures, data processing platforms, middleware architectures, and wireless networks. Topical studies tend to only pass reference to such technologies or to largely focus on one particular technology as part of big data and context-aware ecosystems in the realm of smart cities. Moreover, empirical research on the topic, with some exceptions, is generally limited to case studies without the use of any common conceptual frameworks. In addition, relatively little attention has been given to the integration of big data analytics and context-aware computing as advanced forms of ICT in the context of smart sustainable cities. This endeavor is a first attempt to address these two major strands of ICT of the new wave of computing in relation to the informational landscape of smart sustainable cities. Therefore, the purpose of this study is to review and synthesize the relevant literature with the objective of identifying and distilling the core enabling technologies of big data analytics and context-aware computing as ecosystems in relevance to smart sustainable cities, as well as to illustrate the key computational and analytical techniques and processes associated with the functioning of such ecosystems. In doing so, we develop, elucidate, and evaluate the most relevant frameworks pertaining to big data analytics and context-aware computing in the context of smart sustainable cities, bringing together research directed at a more conceptual, analytical, and overarching level to stimulate new ways of investigating their role in advancing urban sustainability. In terms of originality, a review and synthesis of the technical literature have not been undertaken to date in the urban literature, and in doing so, we provide a basis for urban researchers to draw on a set of conceptual frameworks in future research. The proposed frameworks, which can be replicated and tested in empirical research, will add additional depth and rigor to studies in the field. We argue that big data

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analytics and context-aware computing are prerequisite technologies for the functioning of smart sustainable cities of the future, as their effects reinforce one another as to their efforts for bringing a whole new dimension to the operating and organizing processes of urban life in terms of employing a wide variety of big data and context-aware applications for advancing sustainability.

Keywords Smart sustainable cities · Urban sustainability · Big data analytics
Context-aware computing · Sensors · Models · Data processing
Cloud and fog computing · Middleware

3.1 Introduction

The contemporary city is evolving into becoming computerized on a hard-to-imagine scale due to the rapid development of ICT and its great potential to enhance urban operational functioning and planning. This is increasingly fueled by new discoveries in computer science and data science, coupled with the quick-paced ubiquity and massive use of computational and data analytics within a variety of urban domains to address the complex challenges of sustainability and urbanization facing major cities of the world. This is manifested in the ongoing large-scale design, development, deployment, and implementation of sensor technologies, data processing platforms, cloud computing infrastructures, middleware architectures, and wireless communication networks across urban environments. In parallel, the increasing convergence, prevalence, and advance of urban ICT are giving rise to new faces of cities that are quite different from what has been experienced hitherto on many scales. This is increasingly boosted by data acquisition and storage, information processing, data networking, and intelligence decision support increasingly infiltrating urban systems as operating and organizing processes of urban life. Accordingly, it has been suggested that the potential of monitoring, understanding, and analyzing the city through advanced ICT can well be leveraged in advancing its contribution to the goals of sustainable development. Indeed, the cities that are engaging in the new transition in ICT are getting smarter in how to become more sustainable (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a, b, 2017a, b; Kramers et al. 2014; Shahrokni et al. 2015). Besides, cities as complex systems, with their domains becoming more interconnected and their processes being highly dynamic, rely more and more on sophisticated technologies to realize their potential for responding to the challenge of sustainability and urbanization. Among these technologies are big data analytics and context-aware computing, which are rapidly gaining momentum and generating worldwide attention in the realm of smart sustainable urban development (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Böhlen and Frei 2009; Shepard 2011; Solanas et al. 2014). Big data and context information constitute the fundamental ingredients for the next wave of urban functioning and planning, especially in relation to sustainability. There indeed is a variety of potential uses of big data analytics and context-aware computing to address urban sustainability issues from the source thanks to the deep insights, intelligent decision-making processes, and efficient services delivery enabled by data mining, machine learning, and statistics and related modeling, simulation, and prediction methods. This points to new opportunities and alternative ways to develop, operate, and plan future cities.

The prospect of smart sustainable cities is becoming the new reality with the recent advances in and integration of ICT of various forms of pervasive computing and the underlying cutting-edge enabling technologies. Smart sustainable cities typically rely on the fulfillment of the prevalent ICT visions of the new wave of computing, where everyday objects communicate with each other and collaborate across heterogeneous and distributed computing environments to provide information and services to urbanites and diverse urban entities. The most prevalent forms of pervasive computing in relation to the urban domain are UbiComp, AmI, the IoT, and SenComp (Bibri and Krogstie 2017b). Context-aware behavior and big data capability are considered as prerequisites for realizing the novel applications pertaining to such technologies (e.g., Batty et al. 2012; Bibri and Krogstie 2017a, b; Böhlen and Frei 2009; Coutaz et al. 2005; Schmidt 2011; Shepard 2011; Solanas et al. 2014; Vongsingthong and Smanchat 2014). In all, the expansion of these computing trends as to the underlying technologies and applications are increasingly stimulating smart sustainable city initiatives and projects in ecologically and technologically advanced nations (Bibri and Krogstie 2016a).

The past 5 years have seen extensive investments in ICT infrastructure in cities, which have improved the ability to collect and process large amounts of data throughout urban systems. Virtually every urban aspect, process, activity, and domain is now open to data collection and processing and often even instrumented for data collection and processing: operations, functions, and services in terms of management, control, optimization, enhancement, planning, and so on. At the same time, information is now widely available on external states and events such as urban trends, environmental dynamics, socioeconomic patterns, and so on. This broad availability of data has led to increasing interest in methods and techniques for inferring context knowledge as well as extracting useful knowledge from various forms and sources of data—the realm of context-aware computing and data science—for knowledgeable and strategic decision-making purposes. In all, data are being produced and warehoused, the computing power is available and affordable, the environmental pressures and socioeconomic concerns are alarming, and urbanization challenges are enormous.

The need to understand what constitutes the informational landscape of smart sustainable cities in terms of big data analytics and context-aware computing technologies presents an important topic and new direction of research in the field of smart sustainable cities of the future. The prominence lies in identifying the core enabling technologies and related key techniques and processes required to design, develop, deploy, and implement big data and context-aware applications for advancing urban sustainability. Topical studies tend to only pass reference to such technologies or to largely focus on one particular technology as part of big data and context-aware ecosystems in the realm of smart cities. Moreover, empirical research on the topic, with some exceptions, is generally limited to case studies without the use of any common conceptual frameworks. In addition, relatively little attention has been given to the integration of big data analytics and context-aware computing as advanced forms of ICT in the context of smart sustainable cities. This topic is a significant research area that merits attention, and this endeavor is a first attempt to address these two major strands of ICT of the new wave of computing in relation to the informational landscape of smart sustainable cities. This is to highlight that computers have become far more powerful, networks have become ubiquitous, and techniques and algorithms have been developed that can combine a large number and variety of sensors and connect various datasets to enable broader and deeper computational and analytical solutions than previously possible. The convergence of these phenomena is increasingly enabling many applications of smart computing and data science principles and big data analytics techniques.

The original contribution we make with this chapter is to review and synthesize the relevant literature with the objective of identifying and distilling the core enabling technologies of big data analytics and context-aware computing as ecosystems in relevance to smart sustainable cities, as well as to illustrate the key computational and analytical techniques and processes associated with the functioning of such ecosystems. In doing so, we develop, elucidate, and evaluate the most relevant frameworks pertaining to big data analytics and context-aware computing in the context of smart sustainable cities, bringing together research directed at a more conceptual, analytical, and overarching level to stimulate new ways of investigating their role in advancing urban sustainability. The proposed frameworks, which can be replicated and tested in empirical research, will add additional depth and rigor to studies in the field. We argue that big data analytics and context-aware computing are prerequisite technologies for the functioning of smart sustainable cities of the future, as their effects reinforce one another as to their efforts for bringing a whole new dimension to the operating and organizing processes of urban life in terms of employing a wide variety of big data and context-aware applications for advancing sustainability.

The main motivation for this endeavor is to provide the necessary material to inform relevant research communities of the state-of-the-art research and the latest development in the field of smart sustainable cities in terms of the major technological components of their informational landscape, as well as a valuable reference for researchers and practitioners who are seeking to contribute to, or working toward, the design, development, and implementation of smart sustainable city applications. Especially, with vast amounts of urban data being now available, diverse entities in connection with every urban domain are focused on exploiting data for sustainable advantage.

This chapter consists of six sections. Sect. 3.2 presents a survey of related work in terms of the state-of-the-art research, technological developments, issues, debates, shortcomings, and challenges. In Sect. 3.3, we introduce, describe, and discuss the core big data and context-aware enabling technologies necessary for the functioning of smart sustainable cities of the future, as well as touch upon some key related issues. Sect. 3.4 describes the state-of-the-art analytical and computational processes: data mining and context recognition, and points out basic issues of context-aware applications. In Sect. 3.5, we delve into the urban, computational, technical, and conceptual dimensions of context-aware computing. Finally, we provide our conclusions together with some thoughts in Sect. 3.6.

3.2 Related Work

Research on big data analytics and context-aware computing has been active for more than two decades, resulting in the development of many concepts, approaches, and systems spanning a large number and variety of application domains. Context-aware computing has been researched extensively by the HCI community from various perspectives, including conceptual (e.g., Bibri 2015a; Dey 2000, 2001; Dey et al. 2001), theoretical (e.g., Chen and Kotz 2000; Schilit et al. 1994; Schmidt et al. 1999), critical (e.g., Criel and Claeys 2008; Crutzen 2005; Lueg 2002), and philosophical (e.g., Ulrich 2008). The notion of intelligence alluded to in pervasive computing, in which context awareness has been given a prominent role, has generated a growing level of criticism over the past decade, questioning its feasibility in terms of the inherent complexity surrounding the modeling of all kinds of situations of life (based on the cognitive, affective, emotional, social, behavioral, conversational, and physical subsets of context), as well as challenging its added value as to transforming the way people live (e.g., Bibri 2015a; Crutzen 2005; Gunnarsdóttir and Arribas-Ayllon 2012; José et al. 2010). The whole premise is that it is too difficult to identify and model the specifics of context in real life given their extreme subtlety, subjectivity, and fluidity. In addition, the failure of the original promise of intelligence points to a two-sided problem: the persistent elusiveness of ordinary human reasoning and knowing what people really want and the permissiveness of the definitional looseness of intelligence in terms of what can be expected of the role and scope of artificial reasoning in context-aware interaction paradigms (Gunnarsdóttir and Arribas-Ayllon 2012, p. 12). Context awareness research and development continues to grapple with the problem of what the intelligence in context-aware computing can stand for. Nonetheless, the notion of intelligence as enabled by context awareness capabilities has inspired a whole generation of scholars and researchers into a quest for the immense, fascinating opportunities enabled by the incorporation of computer/machine intelligence into our everyday lives, as well as a large body of research into new techniques and methods for enhancing the sensing, analysis, reasoning, inference, and modeling processes. These have been of extreme value to several other applications (industrial, urban, and organizational) than those directed for human users, in which these processes are inapt to handle the complexity of the nature and scope of inferences (context knowledge) generated by computationally constrained reasoning mechanisms and oversimplified models and on the basis of limited, uncertain, incomplete, or imperfect data collected through sensors. However, the issues stemming from these challenges are under scrutiny and investigation by the research community toward alternative directions (e.g., José et al. 2010), most notably situated intelligence which entails that the cognitive processes and behavior of a situated system should be the outcome of a close coupling between the system (agent) and the environment (user) (see Lindblom and Ziemke 2002). This form of intelligence entails "assisting people in better assessing their choices and decisions and thus enhancing their actions and activities," and the "quest for situated forms of intelligence is seen by several eminent scholars as an invigorating alternative for artificial intelligence research within context-aware computing" (Bibri 2015a, p. 9).

However, the emphasis in this chapter is on the notion of intelligence as enabled by context awareness capabilities but in relation to urban applications rather than human-inspired HCI applications. Urban intelligence in this sense involves enhancing the efficiency of energy systems, communication systems, traffic systems, transportation systems, and so on, as well as the delivery of several classes of city services (utility, healthcare, safety, learning, etc.), based mainly on the physical, situational, and spatiotemporal subsets of context. Especially, building and maintaining complex models of smart sustainable cities functioning in real time from routinely sensed data has become a clear prospect (Batty et al. 2012; Bibri and Krogstie 2017a, b).

In addition, there are several thorough surveys of context modeling and reasoning in pervasive computing (e.g., Bettini et al. 2010; Bibri 2015a; Chen and Nugent 2009; Perttunen et al. 2009). While these surveys tend to differ as regards to both technical emphases (e.g., machine learning techniques, ontological methods, and logical approaches) as well as comparative views on research into modeling and reasoning techniques applied in context awareness, the focus of the analysis and evaluation revolves around the most common approaches into context representation and reasoning and their integration. Integrated approaches have been mainly proposed to overcome the shortcomings (information incompleteness and uncertainty, lack of expressiveness, inflexibility, lack of scalability, etc.) associated with the application of a single approach. For instance, context recognition methods based on probabilistic reasoning inherently suffer from ad hoc static models, scalability, and data scarcity, and the ontology approach allows easy incorporation of machine understandability and domain knowledge, which provide rich expressiveness and facilitates reusability and intelligent processing at a higher level of automation (Chen and Nugent 2009). However, the ontology approach falls short in handling information uncertainty and vagueness (e.g., Bettini et al. 2010). Important to underscore is that most reviews focus on context awareness in relation to the HCI domain, while the literature on context awareness in relation to the urban domain remains scant, in particular as to large-scale applications in the context of smart sustainable cities.

Furthermore, several studies (e.g., Azodolmolky et al. 2005; Paspallis 2009; Schmidt 2002; Soldatos et al. 2007; Strimpakou et al. 2006) have addressed middleware technologies associated with pervasive computing environments and distributed applications. Middleware plays a key role in the functionality of distributed context-aware applications, as it represents the logic glue in a distributed computing system by connecting and coordinating many components constituting distributed applications. Among the key topics addressed in the literature include architectures for pervasive context-aware services in smart spaces in terms of middleware components and prototype applications, middleware for context representation and management in pervasive computing, middleware-based development of context-aware applications with reusable components, middleware for real-time systems, and so forth. There is a need for further research in the area of middleware with regard to the use of large-scale context-aware applications as part of the informational landscape of smart sustainable cities, as well as to the modeling and management of context information in distributed pervasive applications and in open and dynamic pervasive environments.

Research on big data analytics has been active since the mid-1990s (e.g., Fayyad et al. 1996; Laney 2001; Shearer 2000), and several books have been written on the topic from a business intelligence perspective. As a prerequisite for realizing the IoT as an ICT vision of pervasive computing, big data analytics enables to extract knowledge from large masses of data for enhanced decision-making and insights pertaining to a large number and variety of domains. In recent years, the concept and application of big data analytics has been expanded beyond the ambit of business intelligence applications to include urban applications, such as energy, transport, traffic, power grid, healthcare, education, safety, governance, and the quality of life in the context of sustainability (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Bettencourt 2014; Khan et al. 2015; Kumar and Prakash 2014). Moreover, big data analytics has become a key component of the ICT infrastructure of smart sustainable cities (Bibri and Krogstie 2017a, b). In this context, big data analytics targets optimization and intelligent decision support pertaining to the control, optimization, automation, management, and planning of urban systems as operating and organizing processes of urban life, as well as to the enhancement of the associated ecosystem and human services related to utility, healthcare, education, safety, and so on. Additionally, it targets the improvement of practices, strategies, and policies by changing them based on new trends and emerging shifts. In all, the analytical outcomes of data mining serve to improve urban operational functioning, optimize resources utilization, reduce environmental risks, and enhance the quality of life and well-being of citizens.

Furthermore, many reviews or surveys have been conducted in recent years on big data analytics. While they offer different perspectives on, and highlight various dimensions of, the topic, they overlap in many computational, analytical, and technological aspects. Also, they are more often than not oriented toward business intelligence (e.g., Chen et al. 2012; Provost and Fawcett 2013), and tend to put emphasis on different components of big data analytics, such as techniques, algorithms, software tools, platforms, and applications. Chen et al. (2015) provide a systematic review of data mining in technique view, knowledge view, and application view, supported with the latest application cases related mostly to business intelligence. In their survey, Zhang et al. (2016) explore new research opportunities and provide insights into selecting suitable processing systems for specific applications, providing a high-level overview of the existing parallel data processing systems categorized by the data input as stream processing, machine learning processing, graph processing, and batch processing. Singh and Singla (2015) provide an overview of the leading tools and technologies for big data storage and processing, throw some light on other big data emerging technologies, as well as cover the business areas from which big data are being generated. In their review, Tsai et al. (2015) discuss big data analytics and related key and open issues, focusing on how to develop a high performance data processing platform to efficiently analyze big data and to design an appropriate mining algorithm to extract useful knowledge from big data, in addition to presenting some research directions. One of the aspects emphasized in their work is the steps (selection, preprocessing, transformation, mining, and interpretation/evaluation) of the whole process of knowledge discovery in databases (KDD), as summarized by Fayyad et al. (1996). Most of the research articles focus typically more on data mining than other steps of KDD process. Tsai et al. (2015) simplify the whole process into three parts (input, data analytics, and output) and seven steps (collection, selection, preprocessing, transformation, mining, evaluation, and interpretation). Katal et al. (2013) provide a varied discussion covering several big data issues, challenges, tools, characteristics, sources, and best practices in relation to such applications as social media, sensor data, log storage, and risk analysis, areas which pertain to business intelligence. Karun and Chitharanjan (2013) deliver a whole review on Hadoop in terms of HDFS infrastructure extensions, making a comparison of Hadoop Infrastructure Extensions (HadoopDB, Hadoop++, Co-Hadoop, Hail, Dare, Cheetah, etc.) on the basis of scalability, fault tolerance, load time, data locality, and data compression. Chen et al. (2014) review the big data background and the associated technologies, including applications and challenges (in relation to data generation, acquisition, storage, and analysis). However, the literature on big data analytics remains scant in relation to sustainability applications in the context of smart sustainable cities.

In addition, a number of smart city infrastructures (e.g., Al-Hader and Rodzi 2009; DeRen et al. 2015; Khan et al. 2012, 2014a, b, 2015; Khan and Kiani 2012; Nathalie et al. 2012) have been proposed and some of them have been applied in recent years as part of case studies. These infrastructures are based on cloud computing and tend to focus on technological aspects (especially big data analytics, context-aware computing, development and monitoring, etc.), urban management, privacy and security management, or citizen services in terms of the quality of life. There have been no research endeavors undertaken thus far to develop comprehensive or integrated infrastructures for smart sustainable cities as a holistic urban development approach. But there have been some attempts to address some aspects of environmental sustainability in the context of smart cities. For example, Lu et al. (2011) propose a framework for multiscale climate data analytics based on cloud computing. Speaking of the climate in this context, there is still a risk of a mismatch between urban climate targets and the opportunities offered by ICT solutions (e.g., Kramers et al. 2014).

In all, despite the recent increase of research on big data analytics and context-aware computing, the bulk of work tends to deal largely with the domain of business intelligence and the field of HCI respectively in terms of techniques, algorithms, processes, architectures, platforms, and services, thereby barely exploring their relevance and role in the urban domain in terms of advancing sustainability and integrating its dimensions. Especially, a new research wave has started to focus on how to enhance smart city approaches as well as sustainable city models by combining the two urban development strategies in an attempt to achieve the required level of urban operations, functions, designs, and services in line with the goals of sustainable development (e.g., Ahvenniemi et al. 2017; Bibri and Krogstie 2017a, b). In particular, this holistic urban development approach emphasizes the combination of big data analytics and context-aware computing as a set of advanced technologies, techniques, processes, and applications and related platforms, architectures, and infrastructures (Bibri and Krogstie 2017a, b). In other words, these two advanced forms of ICT are being given a prominent role in smart sustainable cities, and the evolving data-centric and context-aware approach is seen to hold great potential to address the challenge of sustainability under what is labeled "smart sustainable cities" of the future (Bibri and Krogstie 2017a, b). The way forward for future cities to advance sustainability and provide the quality of life to their citizens is through advanced ICT that ensures the utilization of big data and the access to contextual information (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Solanas et al. 2014). Local city governments are investing in advanced ICT to provide technological infrastructures supporting AmI and UbiComp, as well as to foster respect for the environmental and social responsibility (Solanas et al. 2014).

3.3 The Core Enabling Technologies of Big Data Analytics and Context-Aware Computing

Like other application areas to which big data analytics and context-aware computing as advanced strands of ICT of the new wave of computing are applied, smart sustainable cities require these two related digital ecosystems and their components to be put in place, spanning different spatial scales in the form of enabling technologies necessary for designing, developing, deploying, and implementing the diverse applications that support, and ideally integrate, the dimensions of urban sustainability. As scientific and technological areas, these two strands involve low-level data collection, intermediate-level information processing, and high-level application action and service delivery (e.g., Bibri 2015a). Worth noting is that as a result of the ongoing effort to realize and deploy smart sustainable cities, which are evolving due to the advance and prevalence of the enabling technologies of ICT of the new wave of computing, all the three areas are under vigorous investigation in the creation of urban environments merging the informational and physical landscapes of such cities for advancing sustainability.

There are many permutations of the core enabling technologies underlying big data analytics and context-aware computing. However, they all pertain to ICT of the new wave of computing, an integration of UbiComp, AmI, the IoT, and SenComp, which will in the near future be the dominant mode of monitoring, understanding, analyzing, and planning smart sustainable cities to improve sustainability (Bibri and Krogstie 2017a, b). It is worth iterating that both big data analytics and context-aware computing share the same core enabling technologies because they are an integral part of ICT of the new wave of computing, as we will elucidate below. As such, they involve unobtrusive and ubiquitous sensing technologies and networks, sophisticated data management and analysis approaches, data processing platforms, cloud computing and middleware infrastructures, and advanced wireless communication technologies. These are to provide solutions in the form of useful and context knowledge for the purpose of achieving the required level of sustainability in the context of smart sustainable cities. Moreover, to have effective and successful solutions on the basis of core enabling technologies, it is required to select a number of design and development priorities in a planned manner prior to any deployment and implementation. For example, it is essential to consider flexible design, quick deployment, extensible implementation, more comprehensive interconnections, and more intelligence (e.g., Chourabi et al. 2012). However, while most of the core enabling technologies are general and apply to many application domains, others remain specific to the urban application domain, specifically to the special requirements and objectives of smart sustainable cities.

3.3.1 Pervasive Sensing for Urban Sustainability

3.3.1.1 Collecting and Measuring Urban Big Data

In the emerging field of smart sustainable urban planning (e.g., Bibri and Krogstie 2017a, b), many scholars in different disciplines and practitioners in different professional domains advocate particularly the inclusion of ubiquitous sensing. Sensor ubiquity is a core feature of smart sustainable cities of the future, which rely on the fulfillment of the prevalent ICT visions of pervasive computing. Within the next 15 years or so, most of the data that will be used to monitor, understand, analyze, and plan the systems of smart sustainable cities will come from digital sensing in the form of observations, transactions, and movements associated with the operating and organizing processes of urban life. Sensors can provide readings on many environmental, social, economic, and physical phenomena. The related data will be available in various forms, with temporal tags and geotags, coupled with a variety of data mining methods and data visualization techniques for displaying and presenting patterns and correlations. A large number of methods for collecting and capturing urban big data from new varieties of digital access are being fashioned and deployed across urban environments. Examples of digital access include the satellite-enabled GPS in vehicles and on citizens, traces left from online transactions processing and related demand-supply situations, online interactions (e.g., social media sites), numerous kinds of websites, and online interactive data systems pertaining to crowdsourcing. Satellite remote-sensing data are also becoming widely deployed, in addition to a variety of scanning technologies associated with the IoT. The convergence of these phenomena are increasingly paving the way for big data analytics (and context-aware computing) to become the dominant mode of urban analytics in relation to urban operational functioning and planning, as well as for exploiting and extending a variety of data mining and machine learning techniques through which the generation of models will be essential in a wide range of engineering solutions for advancing urban sustainability, i.e., improving the contribution of smart sustainable cities to the goals of sustainable development. Such cities are to be monitored, understood, analyzed, and planned across several spatial levels mostly on the basis of data routinely and automatically collected by sensors. With the flourishing smart sustainable urban planning approach (e.g., Batty et al. 2012; Bibri and Krogstie 2017a), pervasive sensing is gaining increased momentum and prevalence as to measuring and collecting data on urban functioning and change in a new way, from the ground up, by means of powerful sensing technologies (motion, behavior, orientation, location, etc.). At present, for instance, sensing urban change from the ground up occurs "through new sensing technologies that depend on hand-held and remote devices through to assembling transactional data from online transactions processing which measure how individuals and groups expend energy, use information, and interact" (Batty et al. 2012, p. 492) with respect to resources. Linking and meshing data from various types of sophisticated measuring devices (RFID, NFC, GPS, laser scanners, etc.) with the automation of standard secondary sources of data and unconventional data no doubt provides a rich nexus of possibilities as to providing new and open sources of data necessary for monitoring and understanding how smart sustainable cities will function in a more effective and efficient way.

At present, the urban environment is pervaded by huge quantities of active devices of diverse kinds and forms to particularly automate routine decisions. The fabric of smart sustainable cities is expected to be, arguably, enveloped with an electronic skin, which can be sewed together and entrenched with even more advanced embedded measuring devices, information processing systems, and communication networks. These include countless intelligent sensing and computing devices and related sophisticated and dedicated techniques and algorithms, as well as widespread diffusion of wirelessly ad hoc, mobile network infrastructures, and related protocols. The primary aim is to build an entirely new holistic system which supports the following:

- The acquisition and coordination of data from multiple distributed sources;
- The management and organization of data streams;
- The integration of heterogeneous data into coherent databases and their warehousing;
- The preprocessing and transformation of data;
- The management and seamless composition of extracted models and patterns respectively;
- The evaluation of the quality of the extracted models and patterns;

- The visualization and exploration of behavioral patterns and models;
- The simulation of the mined patterns and models; and
- The deployment of the obtained results for decision support and efficient service provision.

Regardless of their scales, new sensing and computing devices are projected to be equipped with quantum-based processing capacity, unlimited memory size, and high-performance communication capabilities, all linked by mammoth bandwidth and wireless (Internet) connectivity as well as middleware architectures connecting several kinds of distributed, heterogeneous hardware systems and software applications (Bibri 2015a). All of the above is to be directed for advancing the contribution of smart sustainable cities to the goals of sustainable development. Explicitly, future urban ICT driven by the new wave of computing will result in a blend of advanced applications, services, and computational (data) analytics enabled by constellations of instruments across several spatial scales linked via multiple networks, which can provide a fertile environment conducive to monitoring, understanding, analyzing, evaluating, and planning the sustainability of future cities.

Recent advances in sensor technology have given rise to a new class of miniaturized devices characterized by advanced signal processing methods, high performance, multi-fusion techniques, and high-speed electronic circuits. The trends toward ICT of the new wave of computing, coupled with the evolving concept of smart sustainable cities, are driving research into ever-smaller sizes of sensors capable of powerfully sensing complex and varied aspects of urban life and environment at very low cost. The production of sensing devices with a low cost-to-performance ratio is further driven by the rapid development of sensor manufacturing technologies (e.g., Bibri 2015a). The increasing miniaturization of computer technology is making it possible to develop miniature on-body and remote sensors that allow registering various human and urban parameters without disturbing citizens or interfering with urban activities, thereby the commonsensical infiltration of sensors into daily urban life and environment. This is instrumental in enhancing the computational understanding and data processing of human mobility, urban dynamic processes, and urban operational functioning, a process that entails analysis, interpretation, modeling, and evaluation of big data for enhanced decision-making and deep insights. The new wave of urban computing is about the omnipresence of invisible technology in urban environments and thus citizens' everyday life. Countless tiny, distributed, networked sensor devices will be invisibly embedded in cities for data collection. The research in the area of micro- and nanoengineering (Lyshevski 2001, 2005) is expected to yield major shifts in ICT performance and the way mechatronic components and devices are manufactured, designed, modeled, and implemented, thereby radically changing the nature and structure of sensing devices and thus the way cities will be monitored, understood, analyzed, probed, and planned in the near future.

3.3.1.2 The IoT and RFID Tags

Big data trends are mainly associated with the IoT and UbiComp technologies (e.g., Batty et al. 2012; Bibri and Krogstie 2017a, b; Vongsingthong and Smanchat 2014). These two technologies deal with countless physical objects and different types of sensor devices, and hence the volume of the data generated is huge and the processes and platforms involved in handling these data are complex. Just like UbiComp, the IoT, which "is evolving into more and more sophisticated network of sensor devices and physical objects, is estimated to involve all kinds of everyday objects, including people, roads, railways, bridges, streets, buildings, water systems, electrical networks, vehicles, appliances, goods, machines, animals, plants, soil, and air" (Bibri and Krogstie 2016a, pp. 6–7). The resulting massive repositories of data will be instrumental in improving the contribution of smart sustainable cities to the goals of sustainable development.

Denoting a computationally augmented everyday environment where the physical world and the information world are integrated within the ever-growing Internet infrastructure via a wide range of active and smart data sensing devices, the IoT includes, but is not limited to, RFID, NFC, GPS, infrared sensors, and laser scanners. Overall, the IoT encompasses the following components (Bibri 2015b):

- Tagging things, i.e., RFID and NFC tags are attached to everyday objects and people;
- Sensing things, i.e., sensors act as devices to collect the data from the physical world and transmit them to the informational world;
- Thinking things, i.e., smart things process information, make independent decisions, self-configure, self-regulate, and self-repair; and
- Miniaturized things, i.e., sensing and computing devices based on micro- or nano-electro-mechanical systems (MMES) or (NMES) technology, which are so small to be virtually invisible, embedded in everyday objects to enable them to interact and connect within the smart things thanks to micro-engineering and nanotechnology.

In the IoT, the everyday objects involve devices with intelligence, communication, sensory, and actuation capabilities, e.g., machine-to-machine, vehicle-to-vehicle communication, and people-to-things applications. In other words, the IoT entails sensor and actuator technologies, wireless technologies, and smart things. However, the notion of IoT tends to be identified with RFID, which was seen as a prerequisite for the IoT in the early days and thus the standard method of communication (e.g., Bibri 2015b). RFID tags are being attached to many objects and are expected to be—with further advancement of the IoT predominately entrenched in virtually all kinds of objects around us, handling addressability and traceability, monitoring and controlling devices, and automating process controls and operative tools, and so on (Bibri 2015b). This is at the core of smart sustainable cities of the future in terms of environmental sustainability, i.e., the role of big data analytics in relation to the engineering solutions associated with the optimization, control, and management of urban operational functioning. Likewise, citizens will be inundated by massive amounts of real-time responses based on interacting and networking RFID tags (Bibri 2015b). These tags can be installed near individuals or along the trajectories they follow daily and be read without their knowledge. They can potentially be on everything possessed by citizens and in their surroundings. The way information can be collected in smart sustainable cities of the future will radically change—with further advancements of RFID tags due to the nature of their scalability. The micro- and nanoscale RFID (and other types of sensors) will result in their integration into more and more everyday objects as part of the IoT, enabling people to communicate directly with all sorts of objects, which in turn will communicate with each other and with other people's objects. Holding great potential for disruptive urban transformations, the IoT landscape will consist of trillions of devices and other physical objects connected to the Cloud of Things. To note, RFID had long been the dominant technology until more recently, during the early 2010s, near-field communication (NFC) became more dominant, which is associated with smartphones and proposed as a solution for monitoring and actuating in large-scale deployments within emerging smart sustainable cities.

3.3.1.3 Automated Forms of Big Data

This chapter is concerned with the automated forms of big data, which is the most useful source of big data, whether enabled by the IoT or other forms of ubiquitous computing, when it comes to city development and planning. Such data are generated as an inherent, automatic function of the devices and systems that are widely deployed and networked across urban environments. Indeed, the automated forms of data generation have recently captured the imagination of those concerned with understanding, managing, and planning cities as well as seeking useful insights into urban systems, in particular in the context of environmental sustainability. In particular, there has been an interest in sensor networks and the IoT as well as the tracking and tracing of people and objects (Kitchin 2014). Sensor networks involve an array of tiny, inexpensive sensors and actuators that can be embedded or placed on different structures and systems to measure specific physical outputs or properties pertaining to urban environments, including levels of light, humidity, temperature, heat, acoustics, air pressure, motion, orientation, location, speed, and so on. Active sensors broadcast data at regular intervals over local or wide area networks, or might be equipped with NFC capabilities that enable two-way communication (Hancke et al. 2013). Sensors networks can be used to monitor the use and condition of public infrastructures, such as buildings, roads, parks, facilities, and utility provision, as well as general environmental conditions within smart sustainable cities. In this context, smart sustainable cities entail a blend of advanced applications, services, and computational (data) analytics enabled by constellations of instruments across many spatial scales linked via multiple networks, which can provide a fertile environment conducive to monitoring, understanding, analyzing, and planning urban systems to improve environmental efficiency and sustainability by providing continuous data regarding physical activities and human movements as well as the status of various forms, structures, and processes. As such, smart sustainable cities offer the prospect of an objectively measured, real-time analysis of the processes operating and organizing urban life, which is of paramount importance to advancing environmental sustainability.

There are a number of different means by which the automated forms of data can be generated (Barry et al. 2012; Dodge and Kitchin 2007; Kitchin 2014; Kitchin and Dodge 2011), including sensors:

Capture systems in which the means of performing a task captures data about that task
Digital traces left through purchase of goods and related demand supply situations
Digital devices that record and communicate the history of their own use
Transactions and interactions across digital networks that not only transfer information, but generate data about the transactions and interactions themselves
Clickstream data that record how people navigate through websites or apps
Sensed data generated by a variety of sensors and actuators embedded into objects or environments that regularly communicate their measurements
The scanning of machine-readable objects such as travel passes, passports, or barcodes on parcels that register payment and movement through a system
Machine to machine interactions across the IoT
Automatic meter reading (AMR) that communicates utility usage on a continuous basis
Automated monitoring of public service provision
Uniquely indexical objects and machines that conduct automatic work and are part of the IoT, communicating about their use and traceable if they are mobile (automatic doors, lighting and heating systems, washing machines, security alarms, wifi router boxes, etc.)
Transponders that monitor throughput at toll-booths, measuring vehicle flow along a road or the number of empty spaces in a car park, and track the progress of buses and trains along a route GPS in vehicles and on people RFID tags attached to objects and people Smart tickets that are used to trace passenger travel.

In the domain of urban planning and management, these forms of instrumentation provide abundant, systematic, dynamic, varied, well-defined, resolute, relatively cheap data about urban processes and activities, allowing for real-time analytics and adaptive forms of management and governance (Kloeckl et al. 2012). This is of high relevance to environmental sustainability in the context of smart sustainable cities.

3.3.1.4 Sensor-Based Urban Sustainability Mining

As part of urban reality mining (e.g., Batty et al. 2012; Eagle and Peatland 2006), urban sustainability mining, which pertains to sensing complex environmental and socioeconomic systems by means of ubiquitous sensors embedded throughout urban environments, is a key determinant of how cities developing and responding to the challenge of sustainability are becoming smarter. Mining of urban sustainability depends on dedicated, powerful software applications to log urban infrastructures, spatial organizations and interactions, and mobility and travel behavior as well as ecosystem and public services. The analysis of derived large datasets helps to extract computationally complex activity, behavior, process, and environment models to identify and gain predictive insights into new forms, structures, systems, and processes as to how smart sustainable cities can increase their contribution to sustainability through enhancing urban intelligence functions for decision-making in this regard. Therefore, sensor-based big data have enormous potential to gain new insights into and drive decisions about how sustainability can be better translated into the built, infrastructural, operational, and functional forms of smart sustainable cities across several spatial scales. Further studies in this direction are most likely to enhance mobility, transport engineering, energy engineering, planning, spatial and physical structures, and data-driven characterization of urban functioning in the context of sustainability.

3.3.1.5 Sensor Technologies in Context-Aware Computing

Sensor Types and Sensing Areas in Context-Aware Applications

As with big data analytics, context-aware computing involves a wide variety of sensors. A sensor can be described as a device that detects or measures a physical property or some type of input from the physical environment, and then indicates or reacts to it in a particular way (e.g., Bibri 2015a). The output is a signal in the form of human-readable display at the sensor location or a recorded data that can be transmitted over a network for further processing. Commonly, sensors can be classified according to the type of energy they detect as signals, and include, but are not limited to, the following types:

- Location sensors (e.g., GPS, active badges);
- Optical/vision sensors (e.g., photodiode, color sensor, IR, and UV sensor);
- Light sensors (e.g., photocells, photodiodes);
- Image sensor (e.g., stereo-type camera, infrared);
- Sound sensors (e.g., microphones);
- Temperature sensors (e.g., thermometers);
- Heat sensors (e.g., bolometer);
- Electrical sensors (e.g., galvanometer);
- Pressure sensors (e.g., barometer, pressure gauges);

- Motion sensors (e.g., radar gun, speedometer, mercury switches, tachometer);
- Orientation sensors (e.g., gyroscope);
- Physical movement sensors (e.g., accelerometers);
- Biosensors (e.g., pulse, galvanic skin response measure);
- Vital sign processing devices (heart rate, temperature);
- Wearable sensors (e.g., accelerometers, gyroscopes, magnetometers); and
- Identification and traceability sensors (e.g., RFID, NFC).

While there are different ways of sensing that could be utilized for detecting various features of context, in the realm of smart sustainable cities not all the above are of use in relation to context-aware applications in terms of optimization, control, management, operation, and service delivery associated with sustainability dimensions. How many and what types of sensors can be used in relation to a given context-aware application is determined by the way in which context is operationalized (defined so that it can be technically measured and thus conceptualized) in terms of the number of the entities of context that are to be incorporated in the system based on the application domain, and also whether and how these entities can be combined to generate a high-level abstraction of context (e.g., the physical, situational, behavioral, and social dimension of context). Too often, in relation to both citizens and urban systems, various kinds of sensors are used to detect context.

Acquisition of sensor data about citizens and urban systems (energy, traffic, transport, mobility, etc.) and their behavior and functioning is an important factor in addition to the knowledge domain for analysis of such data by data processing units. In relation to context-aware applications pertaining to citizens, data can be generated from multiple sources, including software equivalents in relation to citizens' devices, such as smartphones, computers, laptops, and other everyday objects. In other words, data are collected and captured from a variety of digital sensors as well as online interactive applications. Observed information about the citizen and urban system' states or situations in conjunction with the dynamic models for the citizen and system' relevant processes serve as input for the process of computational understanding. This entails the analysis and estimation of what is going on in the surrounding environment in the context of smart sustainable cities. Accordingly, for a context-aware application or system to be able to infer high-level context abstraction based on the interpretation of and reasoning on context information, it is first necessary to acquire low-level data from physical sensors (and other sources). Researchers from different application domains within the field of context-aware computing have investigated context recognition for the past two decades or so by developing a diversity of sensing devices (in addition to methods and techniques for signal and data processing, pattern recognition, modeling, and reasoning tasks). Thus, numerous types of sensors are currently being used to detect various attributes of context.

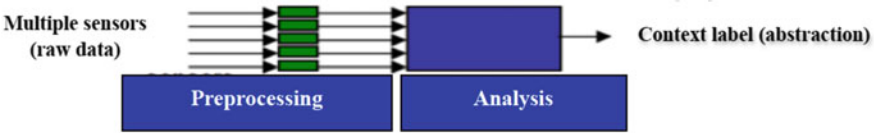

Fig. 3.1 Use of multiple sensors for context awareness

Multi-Sensor Data Fusion and Its Application in Context-Aware Systems

In context-aware computing, underlying the multi-sensor fusion methodology is the idea that an abstraction of context as an amalgam of different, interrelated contextual elements can be generated or inferred on the basis of information detected from multiple, heterogeneous data sources, which provide different, yet related, sensor information. Thus, sensors should be integrated to yield optimal context recognition results, i.e., provide a robust estimation of context. A given dimension of the context, a higher level of the context, can be deduced by using a number of external or internal contexts as an atomic level of the context.

The use of multi-sensor fusion approach in context-aware applications and systems allows gaining access simultaneously to varied information necessary for accurate estimation or inference of context. Multi-sensor fusion systems have the potential to enhance the information gain while keeping the overall bandwidth low (Bibri 2015a). Figure 3.1 illustrates a multi-sensor fusion approach.

3.3.2 *Wireless Communication Network Technologies and Smart Network Infrastructures*

In the context of smart sustainable cities, wireless solutions are set to proliferate in ways that are hard to imagine, as ICT continues to be fast embedded and interwoven into the very fabric of current smart and sustainable cities in terms of their systems and processes in an increasingly computerized urban society. This is a future world of pervasive computing infrastructures and communication networks. Countless sensors will use various wirelessly ad hoc and mobile networks to provide cities with all kinds of data necessary for a wide variety of applications and services. In particular, the widespread diffusion of wireless network technologies will, as a by-product of their normal operations, enable to sense, collect, and coordinate massive repositories of spatiotemporal data pertaining to urban systems, which represent city-wide proxies for all kinds of activities and operating and organizing processes.

Also, smart networks are necessary for big data applications in terms of connecting the components and entities of smart sustainable cities, including diverse citizens' everyday objects (computers, smartphones, cars, house devices, etc.) and city infrastructures and facilities as well as urban departments, authorities, and enterprises. Such networks are intended to provide efficient means for transferring the collected data from heterogeneous and distributed sources to data warehouses where big data are to be stored, coalesced, organized, and integrated for processing and analysis in connection with intelligent decision support systems. This involves transferring responses back to the different citizens' devices and urban entities' systems for the purpose of improving different aspects of sustainability.

In relation to ICT of the new wave of computing, networking is a core enabling technology, in addition to cheap, low-power sensing and computing devices. In this context, the role of networking lies in tying hardware and software systems all together for the functioning of ubiquitous applications and services in urban areas, to draw on Bibri (2015a). Accordingly, many heterogeneous components and devices across dispersed infrastructures and disparate networks need to interconnect as part of vast architectures enabling big data analytics, context-aware computing, intelligence functions, and service provisioning on a hard-to-imagine scale (Bibri 2015a). To put it differently, wireless network technologies are prerequisite for coordinating data as well as linking up many diverse distributed sensing devices and computing components and enabling them to interact in the midst of a variety of hardware and software systems necessary for realizing smart urban environments for advancing sustainability. Wireless technologies, especially satellite-enabled GPS, Wi-Fi, and mobile phone networks enable to sense, collect, and coordinate massive environmental and socioeconomic data representing enormous proxies for the operations, functions, and services of smart sustainable cities and thus powerful physical-environmental and socio-behavioral microscopes (e.g., Bibri and Krogstie 2017b). This may facilitate, by means of big data analytics (data mining and database integration capabilities) which offer the prospect for adding value in terms of massive data analysis and integration, discovering the hidden patterns, correlations, and models that characterize, on the one hand, human mobility and movement as part of daily trajectories and activities of citizens and, on the other hand, physical structures and spatial organizations, which can be instrumental in strategic decision-making associated with urban sustainability planning (see Bibri and Krogstie 2017b). In all, while pervasive sensing and computing infrastructures allow for monitoring, understanding, and analyzing urban life in terms of infrastructure, built form, administration, and ecosystem and human services, pervasive networking infrastructures allow for collecting and coordinating extensive data in terms of how these data are stored, made accessible, and utilized.

In the context of smart sustainable cities, advanced digital networks are crucial to urban operational functioning and planning due to the interrelationships between urban components and domains that are too many to catalogue (transport, mobility, communication, building, energy, environment, water, waste, land use, healthcare, etc.). These are planned to be further heavily networked while the activities relating to these domains to be linked up. The key domains "which currently are being heavily networked involve: transport systems of all modes in terms of operation, coordination, timetabling, utilities networks which are being enabled using smart metering, local weather, pollution levels and waste disposal, land and planning applications, building technologies in terms of energy and materials, health information systems in terms of access to facilities by patients the list is endless. The point is that we urgently need a map of this terrain so that we can connect up these diverse activities." (Batty et al. 2012, p. 493) Especially, the evolving techno-urban contexts are opening spaces for smart sustainable initiatives in domain networking at current times of tension as alternative trajectories are actively being sought due to the challenge of sustainability, which entails creating innovative solutions that further facilitate collaboration among urban domains and hence integrate urban systems.

In parallel, the aim of emerging technological platforms such as UbiComp, AmI, the IoT, and SenComp is to orchestrate and coordinate the various computational entities in the informational landscape of smart sustainable cities and merging it with their physical landscape into an open system that helps diverse urban entities cope with and plan their activities in relation to improving sustainability. Besides, the growing depth, scale, and complexity of urban networks in terms of both domains and technological infrastructures call for developing and coordinating such networks and enhancing their digital capabilities in ways that increase and sustain the contribution of smart sustainable cities to the goals of sustainable development. Advanced wireless technologies are extremely placed to initiate this development and coordination. Moreover, with their ever-growing volume, variety, velocity, and timeliness, data on the state of urban networks as built artifacts as well as on that of their use as part of urban activities and processes provide enormous potential to improve urban operational functioning and planning (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012) in terms of sustainability, efficiency, and the quality of life by exploiting the analytical power of big data for deep insights and enhanced decision-making. To effectively use these data when implementing big data applications in smart sustainable cities requires fostering these data by advanced wireless technologies, especially in relation to real-time applications (see this chapter for further discussion). The rationale is that such applications entail that the data from distributed sources should be aggregated and fused prior to being transferred in real-time to cloud computing infrastructures or data processing platforms for stream processing and decision-making. Important to note is that the aggregation and fusion should be carried out in ways that enable data to remain reliable, accurate, and correct for more effective results and thus beneficial knowledge in terms of decision-making processes. This is in turn of critical importance for maintaining the quality and performance of real-time big data applications in terms of decision-making processes (Mohamed and Al-Jaroodi 2014).

3.3.3 Data Processing Platforms for Big Data Analytics

There is a variety of available data processing platforms for big data analytics, which provide the stream processing required by real-time big data applications in relation to various urban domains. Therefore, data processing platforms are a key component of the ICT infrastructure of smart sustainable cities of the future with respect to big data applications. Among the leading platforms for big data storage, processing, and management include Hadoop MapReduce, IBM Infosphere Streams, Stratosphere, Spark, and NoSQL—database system management (e.g., Al Nuaimi et al. 2015; Fan and Bifet 2013; Khan et al. 2015; Singh and Singla 2015). These platforms work well on cluster systems to meet the requirements of big data applications for smart sustainable cities; entail scalable, evolvable, optimizable, and reliable software and hardware components; and provide high performance computational and analytical capabilities (namely selection, preprocessing, transformation, mining, evaluation, interpretation, and visualization), in addition to storage, coordination, and management of large datasets across distributed environments. As ecosystems, they perform big data analytics related to a wide variety of large-scale applications intended for different uses associated with the process of sustainable urban development, such as management, control, optimization, assessment, and improvement, thereby spanning a variety of urban domains and sub-domains. In all, they are prerequisite for data-centric applications for smart sustainable cities of the future. See Chap. 7 for a detailed discussion of Hadoop MapReduce architecture and related data mining software systems, where this data processing platform represents one of the key components of the informational landscape of smart sustainable cities. The focus on Hadoop MapReduce is justified by the suitability of its functionalities as to handling urban data as well as to its advantages associated with load balancing, cost effectiveness, flexibility, and processing power compared to other data processing platforms. MapReduce has become the primary big data processing system given its simplicity, scalability, and fine-grain fault tolerance (Zhang et al. 2016).

3.3.4 Cloud Computing for Big Data Analytics: Characteristic Features and Benefits

Big data analytics can also be performed in the Cloud (see Chap. 7 for a detailed account and illustration). This involves both big data Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) (e.g., Ji et al. 2012). Having attracted attention and gained popularity worldwide, cloud computing is becoming increasingly a key part of the ICT infrastructure of both smart cities and sustainable cities (e.g., Al Nuaimi et al. 2015; Bibri and Krogstie 2017a; Khan and Kiani 2012; Khan et al. 2014a, 2015; Kramers et al. 2014; Lu et al. 2011) as an extension of distributed and grid computing due to the prevalence of sensor technologies, storage facilities, pervasive computing infrastructures, and wireless communication networks. Especially, most of these technologies have become technically mature and financially affordable by cloud providers. By commoditizing services, low-cost open source software, and geographic distribution, cloud computing is becoming increasingly an attractive option (Kalyvas et al. 2013).

Big data analytics is associated with cloud computing (e.g., Al Nuaimi et al. 2015; Ji et al. 2012; Khan et al. 2013), an Internet-based computing model that is increasingly seen as the most suitable solution for highly resource intensive and collaborative applications as an on-demand network access to a shared pool of computing resources (memory capacity, energy, computational power, network bandwidth, interactivity, etc.) (Al Nuaimi et al. 2015; Kramers et al. 2014; Voorsluys et al. 2011). This entails that computer-processing resources, which reside in the cloud, are virtualized and dynamic. This implies that only display devices for information and services need to be physically present in relation to urban domains where diverse stakeholders (administrators, planners, landscape architects, sustainability strategists, authorities, citizens, etc.) can make use of software applications and services to improve sustainability. Such stakeholders can access cloud-based software applications through a web browser and a lean client (a computer program that depends on its server to fulfill its computational roles) or mobile devices while software tools and urban data of all kinds are stored on servers at a remote location. Indeed, cloud computing model is based on hosted services in the sense of application service provisioning running client–server software locally. In this respect, smart sustainable city applications pertaining to transport, traffic, mobility, energy, public health, civil security, education, and so on reside "in the cloud" and can be accessible per demand. Moreover, the software development platform can be offered in a public, private, or hybrid network, where the cloud provider manages the platform that runs the applications and relieves the cloud clients from the burden of securing dedicated platforms, which would otherwise be very demanding and costly in terms of resources and time. The cloud clients can accordingly benefit from tested, scalable, reliable, and maintainable platforms offered by the cloud provider. Another advantage involves service process optimization through advanced functionalities of software development platforms, namely flexibility, interoperability, reusability, scalability, and cooperation. There is also a great opportunity to slash or minimize energy consumption associated with the operation of ICT infrastructure, especially when it comes to large-scale deployments like in the case of smart sustainable cities as to different departments and service agencies. Beloglazov et al. (2012) develop policies and algorithms that aim at increasing energy efficiency in cloud computing. Energy consumption is way too lower than if all urban entities have their own software development platforms. These are indeed shared by multiple users as well as dynamically reallocated per demand. This approach maximizes the use of computational power and reduces energy usage and thus mitigates GHG emissions associated otherwise with powering a variety of functions as well as data centers dispersed throughout the departments and service agencies of smart sustainable cities. Whether public or private, the cloud provider includes the cloud environment's servers, storage, networking, and data center operations. This implies that the cloud provider has the actual energy-consuming computational resources; users or clients can simply log on to the network without installing anything, thereby curbing energy usage and making the best of the available computational power. Energy efficiency in cloud computing can result from energy-aware scheduling and server consolidation (Andreas et al. 2010). Mastelic et al. (2014) provide a survey on energy efficiency in cloud computing. Also, cloud computing is seen as a form of green computing, especially if it is based on renewable energy like solar panels. It has other intuitive benefits because it relies on sharing of resources and maximizing the effectiveness of the shared resources, thereby reducing the costs otherwise incurred by ICT operations as to human, technical, and organizational resources. In cloud computing, supercomputers in large data centers as a distributed system of many servers are used to deliver services in a scalable manner as well as to enable the storage and processing of vast quantities of data. Cloud computing offers great opportunities for streamlining data processing (Buyya et al. 2010). In all, cloud computing constitutes an efficient and elegant solution in terms of facilitating the huge demand for computing resources associated with big data analytics for decision-making processes in relation to the operational functioning and planning of cities in terms of sustainability. Through the use of cloud computing, smart sustainable cities can accordingly have higher possibilities to perform more effectively and efficiently thanks to the advanced technological features underlying the functioning of cloud computing model.

In addition, cloud computing performs service-oriented computing. In this regard, it can rapidly process large and complex data produced from urban activities and simultaneously serve citizens in relation to healthcare, education, housing, utility, and so on, providing a kind of integrated and specialized center for information services to both the general public and urban departments across various urban domains. In light of this, with reference to smart sustainable cities, cloud computing has the ability to run smart applications on many connected computers and smartphones at the same time for different purposes associated with increasing sustainability performance.

In sum, among the key advantages provided by cloud computing technology include cost reduction, location and device independence, virtualization (sharing of servers and storage devices), multi-tenancy (sharing of costs across a large pool of cloud provider’s clients), scalability, performance, reliability, and maintenance. Therefore, opting for cloud computing to perform big data analytics in the realm of smart sustainable cities remains thus far the most suitable option for the operation of infrastructures, applications, and services whose functioning is contingent upon how urban domains interrelate and collaborate, how efficient they are, and to what extent they are scalable as to achieving and maintaining the required level of sustainability.

3.3.5 Fog and Edge Computing

3.3.5.1 Fog Computing Versus Cloud Computing

Fog computing (Numhauser 2012), also known as fogging or edge computing, can be viewed as an alternative computing model to cloud computing in the context of the IoT and its underlying big data analytics. It is an architecture that uses one or more collaborative near-user edge devices to carry out a substantial amount of storage (rather than stored primarily in cloud data centers), communication (rather than routed over the Internet backbone), control, configuration, measurement, and management (rather than controlled primarily by network gateways). Although both fog computing and cloud computing provide storage, applications, and data to end-users, fog computing has a bigger proximity to end-users and bigger geographical distribution (Bonomi et al. 2012). On the data plane which constitutes one of the components of fog networking, fog computing enables computing services to reside at the edge of the network as opposed to servers in a data center like in cloud computing. Accordingly, fog computing emphasizes proximity to end-users and client objectives, dense geographical distribution, and local resource pooling, latency reduction and backbone bandwidth savings to achieve better quality of service (QoS) (Brogi and Forti 2017), as well as edge analytics/stream mining resulting in redundancy in case of failure (Arkian et al. 2017). Moreover, it is said that fog computing is a medium weight and intermediate level of computing power, whereas cloud computing can be a heavyweight and dense form of computing power, as it uses a network of remote servers hosted on the Internet to store, manage, and process data, rather than a local server. Mist computing is a lightweight form of computing power that resides directly within the network fabric at its extreme edge using microcomputers and microcontrollers to feed into fog computing nodes and potentially onward toward the cloud computing platforms. Furthermore, fog computing extends cloud computing to the edge of an organization or city's network. In this context, it facilitates the operation of computation, storage, communication, and networking services between end devices and cloud computing data centers, and entails the distribution of the related resources and services on or close to devices and systems in the control of end-users (Zhang 2016; Ostberg et al. 2017).

In the context of smart sustainable cities, fog computing can be seen in big data structures as well as in large cloud systems, making reference to the growing difficulties in accessing information objectively. This results in a lack of quality of the obtained content. The effects of fog computing on cloud computing and big data applications may vary; however, a common aspect that can be extracted is a limitation in accurate content distribution, an issue that has been tackled with the creation of metrics that attempt to improve accuracy (Numhauser 2013). Cloud computing performs complex and full data validation, storing, processing, and processing (big data analytics), whereas fog computing carries out more complex data processes, namely validation, storage, and forwarding.

In fog computing, transporting data from things to the cloud requires several components (steps), namely:

- The automation controller for automating the physical assets or things,
- The server or protocol gateway for receiving the data from the control system program and then converting the data into a protocol Internet systems, and
- The fog node or the IoT gateway on the LAN to which the data are to be sent for performing higher level processing and analysis. This system filters, analyzes, processes, and may even store the data for transmission to the cloud or WAN at a later date.

The disadvantage of fog computing is the extent of complexity it brings to the computation, storage, and networking as part of the overall architecture. This has implications for the time taken to perform analysis as well as the cost of ownership since physical things have to be secured and maintained due to the fact that fog computing pulls processing capabilities to a fog as a form of decentralized location.

3.3.5.2 Fog and Edge Computing for the IoT

Fog and edge computing models have been developed to respond to the sheer, monumental increase of data bandwidth required by the end devices that underpin the IoT. The concept has indeed been fueled by the explosion of the IoT, a computing paradigm that has made it necessary to process the generated data much closer to the source in real time, pushing the cloud closer to the requester as a way to minimize latency as well as to increase quality. Fog networking supports the IoT concept, in which most of devices and everyday objects are to be connected to each other, such as smartphones, wearable devices, connected vehicle and augmented reality using devices (e.g., Bonomi et al. 2012). The fundamental objective of the IoT is to obtain and analyze data from physical assets or things that were previously disconnected from most data processing tools. This relates to sensor-based big data applications pertaining to smart sustainable cities in the context of environmental sustainability. The urban big data are generated by physical assets or things deployed at the very edge of the network that perform specific tasks to support environmental sustainability. The IoT is about connecting the unconnected devices (things) and sending their data to the cloud or Internet to be analyzed. In traditional IoT cloud architecture, all these data from physical assets or things are transported to the cloud for storage and advanced analysis associated with big data applications. The IoT devices generate a constant stream of data that has to be validated, analyzed, and processed in real time. Data validation needs to, with the explosion of the IoT devices, take place closer to the requester. In this regard, fog and edge computing can crunch through data at a fast pace compared to cloud computing (data center). It moreover allows disconnected validation of data, a feature that lowers bandwidth costs, as it helps reduce the total amount of end to end bandwidth needed.

3.3.5.3 Fog and Edge Computing: Commonalities and Differences

Fog and edge computing in smart sustainable city applications are network and system architectures that attempt to collect, analyze, and process data from physical assets closer to the requester and more efficiently than traditional cloud architecture. In light of this, these two computing models are closely related and aimed at reducing latency cost and increase quality, to reiterate. Both are able to filter data prior to reaching a big data lake for further consumption, thereby decreasing the amount of data that need to be processed. Data reduction is an important process of big data analytics techniques. Though there is a key difference between the two concepts fog and edge computing architectures share similar objectives, namely reducing the amount of data sent to the cloud, decreasing network and Internet latency, and improving system response time in remote applications. Also, data in both are generated from the same source-physical assets like sensing devices which perform a task in the physical world, i.e., sensing the world around them as related to environmental phenomena, dynamics, changes, parameters, patterns, and so on in the context of smart sustainable cities. There is such a wide variety and large number of physical things augmented with sensing, actuation, and communication capabilities that make up the IoT system as part of the overall ICT infrastructure of smart sustainable cities. In addition, both involve pushing processing and intelligence capabilities down closer to where the IoT data originates—at the network edge—and the physical things are connected together. The key difference between the two architectures lies in exactly where such capabilities are placed, i.e., the location of the devices. In fog computing, intelligence and computing power are pushed down to the local area network (LAN) level of network architecture, processing data in a fog node or the IoT gateway. Whereas in edge computing, data validation and processing intelligence together with communication capabilities of an edge gateway are pushed directly into central edge devices like routers. This is crucial to strengthening security measures by implementing encryption in the local network before the data traverse through insecure or unprotected parts of the Internet. Furthermore, the need for validating and preprocessing data either within a fog (a LAN) or an edge (a gateway device) emanates from the fact that it is not sensible to install a full data center on a plane. In all, the basic idea of fog and edge computing is to move data logic (data validation) to an outer ring of processing capabilities.

In fog computing, transporting data from things to the cloud requires several components (steps), namely:

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- The fog node or the IoT gateway on the LAN to which the data are to be sent for performing higher level processing and analysis. This system filters, analyzes, processes, and may even store the data for transmission to the cloud or WAN at a later date.

Hence, fog computing involves in the context of the IoT many layers of complexity and data conversion (e.g., Bonomi et al. 2012). To move data from the physical world of assets across the domains of smart sustainable cities into the digital world of ICT requires many links in a communication chain, which fog computing architecture relies on and in which each link is a potential point of failure. This is in contrast to edge computing which simplifies the communication chain and decreases the number of potential points of failure in the IoT-enabled big data applications. Indeed, edge computing is a direct response to the mammoth increase of bandwidth required by the end devices that underpin the IoT, to reiterate. In addition, edge computing saves time by reducing the complexity associated with system and network architecture as well as streamlining IoT communication. This feature is of crucial importance to the success of the IoT-enabled big data applications in the context of smart sustainable cities.

In edge computing, the focus is on the automation controller into which physical assets like sensors are physically wired, and which automate things by executing an onboard control system program. Intelligent programmable automation controllers with edge computing capabilities collect, process, and analyze data from the physical assets they are linked to. Subsequently, they use edge computing capabilities to determine what data should be stored locally or sent to the cloud for further analysis.

3.3.6 Middleware Infrastructure for Context-Aware Computing: Characteristics and Functions

Middleware infrastructure is associated with pervasive computing environments and distributed applications. These encompass UbiComp, AmI, and SenComp environments and applications. Middleware infrastructure (e.g., Azodolmolky et al. 2005; Soldatos et al. 2007; Strimpakou et al. 2006) plays a key role in the functionalities of complex distributed applications, including context-aware applications. Thus, context-aware computing, which is associated with UbiComp, AmI, and SenComp, requires middleware infrastructure to operate. This infrastructure can also run on cloud computing (Platform as a Service (PaaS) and Infrastructure as a Service (IaaS))—i.e., cloud middleware.

Middleware infrastructure represents the logic glue in a distributed computing system, as it connects and coordinates many components constituting distributed applications. This occurs, more specifically, "in the midst of a variety of heterogeneous hardware systems and software applications needed for realizing smart environments and their proper functioning. To put it differently, in order for the massively embedded, distributed, networked devices and systems, which are invisibly integrated into the environment, to coordinate require middleware components, architectures, and services. Middleware allows multiple processes running on various sensors, devices, computers, and networks to link up and interact to support [and maintain the operation of context-aware applications needed by citizens and urban entities to cope with and perform their] activities wherever and whenever needed." (Bibri 2015a, p. 50). Indeed, it is the ability of multiple, heterogeneous hardware and software systems to cooperate, interconnect, and communicate seamlessly across disparate networks that create smart environments rather than just their ubiquitous presence and massive use. In the context of smart sustainable cities, such systems in their various forms (e.g., sensors, smartphones, computers, databases, data warehouses, application integration methods, application servers, web servers, context management systems, and messaging systems) are highly distributed, interoperable, and dynamic, involving a myriad of embedded devices and information processing units "whose numbers are set to increase by orders of magnitude and which are to be exploited in their full range to transparently provide services on a hard-to-imagine scale, regardless of time and place" (Bibri 2015a). This in turn allows for the functioning of context-aware applications across the diverse domains of smart sustainable cities.

There are different approaches to conceptualizing middleware. According to Schmidt (2002), middleware consists of the following four distinct layers based on their intended functionality:

(1) Host-infrastructure middleware,
(2) Distribution middleware,
(3) Common middleware services, and
(4) Domain-specific middleware services.

Another conceptualization of middleware entails a common multilayer architecture that provides particular functionalities and constitutes the basis for upper layers of more abstraction. It includes the following components:

- Infrastructure and communications (messaging services) pertaining to entities of the upper layer;
- Services and agents related to semantic descriptions;
- Middleware services concerned with the software environment; and
- Intelligence associated with the coordination of application actions and involving a number of devices in the environment.

As regards to some of its characteristic features compared to cloud computing, middleware-based architectures entail reusable software infrastructure that resides between the application programs (in this case context-aware applications) and the underlying hardware and operating systems. That is to say, middleware sits between the kernel and applications. Incidentally, the functionality of network protocol stacks (TCP/IP) was previously provided separately by middleware, but nowadays is integrated in every operating system. Moreover, middleware simplifies and supports the development of complex distributed applications, using such tools as web servers, application servers, messaging systems, and content management systems. These applications collaborate with, or leverage services from, other disparate applications that are systematically tied using methods of application integration. In addition to handling the distribution and heterogeneity of computing resources associated with the logic of context-aware applications in this context, middleware is intended to bridge the gap between the applications and the underlying lower level hardware and software infrastructure to ensure and boost coordination, cooperation, interconnection, dynamicity (e.g., sensors join and leave AmI infrastructure in a dynamic fashion), and interoperability of the different components of distributed applications (e.g., Bibri 2015a; Gokhale et al. 2002; Paspallis 2009). These functionalities are in fact necessary for supporting scalable systems as well as highly heterogeneous and distributed components, such as agents and services. In relation to this, middleware support and deploy data-centric distributed systems (e.g., network-monitoring systems, sensor networks, and dynamic Web) whose ubiquity creates large application networks spreading over large geographical areas (Bibri 2015a). Especially, AmI and UbiComp infrastructures are highly dynamic and involve high degree of heterogeneity (e.g., Johanson et al. 2002). As to interoperability, for instance, context-aware applications run on different operating systems, thereby the role of middleware in enabling interoperability between applications by supplying services for exchanging data in a standard way. Indeed, in the realm of context-aware computing, which entails distributed processing in the sense of multiple applications being connected to create larger applications over a network, middleware provides services beyond or more than those available from the operating system of these applications to enable the various elements of the underlying distributed system to communicate and manage data, thereby serving as a kind of a software glue. Therefore, distributed processing is empowered by middleware for transferring signals from various sources and for realizing information fusion from multiple perceptive components (Azodolmolky et al. 2005).

Middleware and cloud computing infrastructures differ in their technical details as to how they provide application services and which kind of services they are concerned with, as well as in the characteristic features of their operation and complexity. Yet, they denote computing models where machines in large data centers across distributed environments can be used to deliver a variety of services and meet the needs of different urban constituents in terms of the use of big data and context-aware applications for improving sustainability. Hence, both are prerequisites for the operation of smart sustainable cities. This is anchored in the underlying assumption that big data and context-aware applications are an integral part of ICT of the new wave of computing, and smart sustainable cities typically rely on the fulfillment of its underlying visions.

3.3.7 Big Data Management

Given the volume, variety, and velocity characterizing big data, effective and suitable big data management tools are extremely important to ensure a useful utilization of big data in terms of analytics and the related results and inferences. Accordingly, as smart sustainable cities involve the generation of large, varied, and time-based data pertaining to such urban domains as transport, traffic, mobility, energy, environment, land use, healthcare, education, and so on, huge data management capabilities are necessary to allow to make sense of these data. Especially the field of urban sustainability necessitates these domains to be interrelated and coordinated to collaborate and inform one another. In this respect, the urban data are generated on a regular basis in the form of massive repositories, i.e., huge amounts of data on environmental and socioeconomic aspects of urban areas, which provide a powerful microscope of, and a real-time view of what is happening in, the city as to sustainability performance across several spatial scales and over multiple temporal scales. A successful utilization of these valuable data in smart sustainable cities requires advanced big data management tools and methods. This entails the development and implementation of scalable and powerful architectures, best practices, and dedicated computational processes for properly managing data lifecycle throughout various phases of data use, particularly in terms of addressing the issue of variety and velocity, i.e., recognizing their different formats and sources as well as organizing, cataloguing, classifying, and controlling all classes and structures of data. In addition, for smart sustainable city applications, big data management should provide tools for scalable handling of massive data to serve real-time applications and support offline applications (see Al Nuaimi et al. 2015). For the interested reader, there are several studies that have addressed the topic of big data management (e.g., Xiaofeng and Xiang 2013; Borkar et al. 2012; Chaudhuri 2012) in terms of concepts, approaches, techniques, and challenges.

3.3.8 Advanced Big Data Analytics Techniques and Algorithms

In smart sustainable cities, big data analytics should involve highly sophisticated and dedicated techniques and algorithms (data mining, machine learning, statistics, database query, etc.) that can perform complex computational processing of data for timely and accurate decision-making purposes. Traditional techniques and algorithms are inadequate for handling big data associated with smart sustainable city applications due to their high-volume, high-variety, and high-velocity. Urban big data necessitate high-speed processing power and high performance to obtain useful results necessary to enhance decision-making pertaining the urban operational functioning and planning of smart sustainable cities. Therefore, existing techniques and algorithms need to be improved in ways that can handle the extreme volume of data, the wide variety of data types, and the time constraints on data processing. In particular, data mining algorithms and techniques are by far unfit for handling big data because they are designed to deal with limited and well-defined datasets (e.g., Wu et al. 2014). In the context of smart sustainable cities, such techniques and algorithms need to be exploited, enhanced, and extended in order to yield the desired outcomes in terms of extracting the useful knowledge (patterns and correlations) necessary for improving sustainability performance (see, e.g., Batty et al. 2012; Bibri and Krogstie 2017a, b). Alternative or novel solutions in this regard are required to be designed with more scalability and flexibility to handle dynamic and real-time aspects of big data applications for smart sustainable cities, among other things. Moreover, they are to operate as an integral part of cloud computing (PaaS) and thus collaborate across diverse networks for aggregating, fusing, processing, analyzing, and visualizing data collected from countless sensing devices from multiple sources, stored in massive repositories, and coordinated through smart networks. In other words, they need to work effectively across disparate networks, dispersed infrastructures, distributed geographical locations, and heterogeneous computing environments, as well as to be capable of operating in highly scalable and dynamic settings, to reiterate. New approaches to storing, managing, coordinating, and analyzing big data, in particular in relation to smart sustainable city applications should rely on advanced artificial intelligence programs and machine learning techniques. This is in contrast to loading big data into traditional relational databases for analysis, a process that relies on data schema and is time consuming and computationally expensive. For a detailed account of big data analytics techniques and algorithms from a general perspective, the interested reader might want to read Provost and Fawcett (2013). See Chap. 4 for a relevant account of data mining techniques and algorithms. Also, Chen et al. (2015) provide a thorough survey of data mining techniques and algorithms.

3.3.9 Privacy Mechanisms and Security Measures

It is highly important to ensure that all technological components associated with big data and context-aware applications for smart sustainable cities are supported by security measures and privacy mechanisms. It is essential to control big data (Forrester Research 2012) and context data (Bibri 2015b). Massive repositories of urban data are at stake, and failure to protect these data will pose risks and threats to the functioning of smart sustainable cities as well as to the safety and well-being of their citizens on several scales. Therefore, security measures and privacy mechanisms should be at the core of urban policy and governance practice associated with the design, development, deployment, and implementation of big data and context-aware applications within smart sustainable cities. Any attempt of an unauthorized access, malicious attack, or abuse of information on citizens, infrastructures, networks, and facilities can compromise the integrity of such applications and related services. Smart sustainable cities generate colossal amounts of data on virtually every urban process, which are to be stored, processed, and shared. Urban environments "are now being continually forged and re-forged in [sensorial,] informational, and communicative processes. It is a world where…cities think of us, where the environment reflexively monitors our behavior" (Crang and Graham 2007, p. 1), including whether and the extent to which we behave in a sustainable way through the activities we perform in cities.

However, it is commonly held views that the more cities think of and know about us and technologies monitor urban environments and collect information, "the larger becomes the privacy threats, and the larger… the networks, the higher the security risks" (Bibri 2015b, p. 218). When sensing, computing, and networks become ubiquitous, "when everything is embedded with intelligence and connected to everything else via the Internet and other networks, the threats and vulnerabilities will become even greater than they are nowadays." (Bibri 2015b, p. 218) There is a need for technological safeguards as a response to the risks posed by the emerging urban trends of big data analytics and context-aware computing. Clear guidelines, recommendations, and requirements must be identified and put in place in relation to big data and context-aware applications for smart sustainable cities. Among the privacy mechanisms proposed thus far for addressing the issue of privacy include "anonymity, pseudonymity, unlinkability, and unobservability," yet they need to be "fully developed, evaluated, and instantiated in their operating environment to test their performance—how well they work" (Bibri 2015b). Big data and context-aware applications for smart sustainable cities require the development of more robust, if not unconventional, privacy-protecting safeguards by considering the most likely ways through which the information from different urban domains can be leaked and breached. As regards to the security, the scientific challenges "include methods supporting the evaluation of risk exposure…, security design principles to enable control of the risk exposure, methods for… security analysis, security of big [and context] data…, secure cloud of physical and smart things, cyber physical systems security, lightweight security solutions, authentication and access control…, identification and biometrics…, cyber-attacks detection and prevention, and so on." (Bibri 2015b, pp. 223–224) While information security risks are of diverse nature, including "modification, destruction, theft, or lack of availability of computer assets such as hardware, software, data, and services" (Straub and Welke 1998, p. 442), integrity and confidentiality—i.e., protection of information from modification and unauthorized use—should be more of focus as categories of security threats in the ICT of the new wave of computing networks than in the traditional networks (Bibri 2015b). This is due to the fact that there is "possible conflict of interests between communicating entities; network convergence; large number of ad hoc communications; small size and autonomous mode of operation of devices; and resource constraints of mobile devices" (Wright et al. 2007, p. 50). Of critical importance, nevertheless, is to develop a new security paradigm which supports advanced features of context-aware technology, as conventional password entry schemes using traditional input devices have proven to be vulnerable to attacks. To address these issues, new research endeavors are focusing on such new techniques as authenticating with minds; pointing and selection using gaze and keyboard; and gaze-based user authentication (Bibri 2015b). In relation to this, Wright et al. (2007) suggest some research directions, including "improving access control methods by multimodal fusion, context-aware authentication and unobtrusive biometric modalities," and "increasing security by detection of unusual patterns."

3.3.10 Standards and Open Standards

It is important to follow standards when it comes to data integration to make sense of data proliferation as well as to ensure data quality. Standard rules are also needed for evaluating the accuracy and correctness of data and for dealing with such issues as uncertainty and incompleteness of data, especially in relation to real-time big data (and context-aware) applications which require the data to be described using advanced models of the very urban systems that data are associated with in case of missing and inconsistent data. It is of equal importance to set and comply with standard rules with respect to new applications for advancing urban sustainability to achieve seamless integration between the available urban systems (in terms of infrastructural, physical, operational, and functional forms) and the introduced big data (and context-aware) applications across diverse urban domains. In this regard, the way forward is to carry out a thorough investigation of the different urban entities and actors as well as the infrastructure, built form, administration, and ecosystem and human services as to their operation as urban systems to strategically assess the benefits of new solutions and the readiness of urban stakeholders to join any smart movement associated with improving urban sustainability. In light of such investigation, new practices, regulations, and standard models of design and rules can be developed for big data and context-aware applications for smart sustainable cities.

Concerning other areas related to big data and context-aware applications for smart sustainable cities, it can be advantageous to pursue open standards for designing and implementing solutions with respect to various urban domains, as such applications involve large-scale and heterogeneous data systems. The rationale behind open standards in this respect is to provide some flexibility for scaling up, upgrading, improving, and maintaining applications for smart sustainable cities, as new challenges are most likely to emerge and thus operative solutions may become inadequate to handle potential complexities and difficulties as to translating sustainability into the built, infrastructural, operational, and functional forms of such cities.

3.4 The State-of-the-Art Analytical and Computational Processes

3.4.1 The Process of Data Mining

One of the fundamental concepts of data science is the automated extraction of useful knowledge from large masses of urban data to solve urban sustainability problems (physical, environmental, social, and economic) related to diverse urban domains, which can be treated systematically by following a set of reasonably well-defined stages, i.e., several codifications of the process of data mining, most notably the Cross Industry Standard Process for Data Mining (CRISP-DM). This process provides a framework to structure urban thinking about data analytics problems related to different dimensions of sustainability, as in smart sustainable urban planning practice, it is important to devise analytical solutions based on careful analysis and evaluation of the relevant problems using high-powered analytical and evaluative tools, as well as creativity, common sense, and specialized knowledge. Therefore, structured thinking about urban data analytics is of significance to supporting decision-making processes concerning different dimensions of sustainability within almost all urban domains. A codification of the data mining process, drawing on Shearer (2000), involves the following steps:

1. Urban sustainability problem understanding,
2. Data understanding,
3. Data preparation,
4. Model building,
5. Results evaluation, and
6. Results deployments.

See Chap. 4 for a detailed discussion of these steps with illustrative examples of urban sustainability problems (questions). Applicable to the domains of smart sustainable cities, the process of data mining emphasizes the idea of iteration. This implies that solving a particular urban sustainability problem may require going through the process more than once.

The objective of the process of data mining (see Chap. 4 for a detailed discussion with illustrative examples) is to discover new knowledge in large masses of urban data pertaining to different sustainability dimensions to improve the environmental and socioeconomic performances of smart sustainable cities. Accordingly, such process is concerned with solving problems related to the spatial, physical, infrastructural, operational, and functional forms of such cities in the context of sustainability. For an optimal outcome in the case of spatial data mining, for example, it is invaluable to integrate different methods (spatial analysis, spatial statistics, fuzzy logic, probability theory, cluster analysis, etc.), especially these methods are not mutually exclusive (DeRen et al. 2015). As to the spatial data, they include such features as spatial, massive temporal, massive multidimensional, and complex (Li et al. 2006).

3.4.2 The Process of Context Recognition

Smart sustainable cities as intelligent urban environments provide important contextual information that should be exploited in such way that the intelligent actions taken by diverse context-aware applications related to both citizens and systems within such environments must be relevant to the current context. Context recognition is the process whereby various contextual features of the urban environment (physical, environmental, spatiotemporal, socioeconomic, situational, and behavioral) are detected, monitored, analyzed, and interpreted to generate relevant inferences though reasoning processes. It encompasses many different tasks, namely context modeling in terms of knowledge representation and reasoning, contextual features monitoring, data processing and pattern recognition, and intelligent decision-making and action-taking. The whole process involves the following steps:

1. Create computational models of contexts pertaining to the citizen and urban system (energy, traffic, transport, building, mobility, healthcare, utility, etc.) in a

way that allows software agents/systems to perform reasoning and manipulation;
2. Monitor and capture relevant contextual features depending on the application domain;
3. Process observed information (low-level contextual data) through aggregation and fusion to generate a high-level abstraction of context;
4. Decide which algorithm or a set of algorithms to use. This is based on the way in which contexts as related to some aspects of sustainability are modeled, represented, and reasoned about (often based on a hybrid modeling approach);
5. Carry out pattern recognition and generate inferences; and
6. Make a timely decision and take the most appropriate action accordingly.

These steps can be applicable to the recognition of different dimensions of context, e.g., situational, spatiotemporal, behavioral, and environmental. Researchers from different application domains in the field of context-aware computing have investigated context recognition for the past two decades by developing and enhancing a variety of approaches, techniques, and algorithms in relation to a wide variety of context-aware applications (Bibri 2015a).

3.4.3 Basic Issues of Context-Aware Applications

Placing reliance on context knowledge through recognizing, interpreting, and reasoning about contextual data from sensors to infer a high-level abstraction of a context and react to it by performing application actions to support citizens or operate urban systems is a process that is nontrivial and often extremely difficult to realize, regardless of the application domain in the context of smart sustainable cities. A central concern, in particular, is the issue of linking the perceived context (observed contextual data) to application behaviors-firing context-dependent actions. Drawing on Bibri (2015a), there are four basic issues related to generic contextual model that are central and necessary to be addressed to create context-aware applications pertaining to smart sustainable cities:

1. *Perception as precondition.* To create context-aware applications it is inevitable to provide them with perception capabilities as to various types of urban context, including the domains of sensing, abstraction, and modeling (conceptualization and representation);
2. *Finding and analyzing situations pertaining to citizens and urban systems that are of relevance to* context-aware *applications.* When such applications are based on some kind of implicit interaction, it becomes a central problem to find the situations that should have an effect on their behavior;
3. *Abstracting from situations to context.* Describing a situation is already a high-level abstraction of context. To describe what should have an influence on

application classes of situations have to be selected which will influence the behavior of context-aware applications; and

4. *Linking context to behavior*. To describe application classes of situations and in a more abstracted way, contexts must be linked to actions carried out by context-aware applications.

3.5 Context-Aware Computing and Its Computational, Technical, and Urban Dimensions

3.5.1 Context Awareness Technology for Urban Sustainability

The focus in this chapter is on the physical, situational, spatiotemporal, and socioeconomic features of the citizen context as to the interactive applications pertaining to healthcare, education, learning, security, accessibility, utility, and so forth, as well as on the physical, operational, environmental, and spatiotemporal aspects of the urban system context as to the operating and managing processing relating to energy, transport, traffic, mobility, power grid, and so on. Thus, the capabilities of context awareness technology directed for enhanced decision-making and service delivery processes are of high relevance to smart sustainable cities in terms of urban analytics associated with sustainability. The adaptive and responsive features of context-aware applications and systems constitute forms of urban intelligence in its wider sense. One of the cornerstones of ICT of the new wave of computing (UbiComp, AmI, and SenComp) is the intelligent behavior of applications and systems in response to the different contexts of citizens and urban systems (situations, events, locations, settings, behaviors, activities, etc.).

Context-aware computing is becoming increasingly a key component of the infrastructure of smart sustainable cities (e.g., Bibri and Krogstie 2017a, b; Kamberov 2015; Solanas et al. 2014) and future smart cities (e.g., Riva et al. 2008). Having access to context information in smart sustainable city applications plays a key role in supporting decision-making processes pertaining to sustainability (e.g., Al Nuaimi et al. 2015; Bibri and Krogstie 2017a, b; Solanas et al. 2014). As one of the prerequisites, technologies for enabling ICT of the new wave of computing and for realizing the ICT visions of pervasive computing, context awareness aims to “support human action, interaction, and communication in various ways wherever and whenever needed” (Bibri 2015a, p. 1) by enabling sensorily and computationally augmented urban environments to provide the most efficient services to citizens and intelligent support to urban actors within a variety of settings (e.g., Bibri and Krogstie 2017a, b). Entailing a set of advanced computational functionalities, context-aware applications are able to, by relying on context knowledge, control over processes and automate operative tools as well as provide services and support decision-making needs, thereby exhibiting intelligent behavior. In short, context awareness technology is associated with control, automation, optimization, and management, as well as with the adaptation of services. The system behavior's adaptation is based either on pre-programmed heuristics or real-time reasoning capabilities. The purpose of machine learning and reasoning is to monitor the behaviors of urban systems and citizens and the changes in their environment using sensors of many types to generate inferences (high-abstractions of contexts) based on reasoning mechanisms, and then use physical actors (actuators) or application actions to react and pre-act accordingly in ways that are more constructive in terms of enhancing urban operations, functions, and services in line with the goals of sustainable development. The widespread adoption of diverse sensors within cities provides interactions through opportunistic and people-centric sensing (Lane et al. 2008; Manzoor et al. 2014). In this regard, context-aware applications can monitor what is happening in urban environments, analyze, interpret, and respond to them in a variety of ways—be it in relation to smart energy, smart street lights, smart traffic, smart transport, smart mobility, smart education, smart healthcare, or smart safety—across several spatial and temporal scales (e.g., Bibri and Krgostie 2016b). It is becoming increasingly evident that smart urban environments based on context-aware technologies—especially within smarter cities as future forms of smart cities, namely ambient cities, sentient cities, ubiquitous cities, Internet-of-everything, and real-time cities (e.g., Batty et al. 2012; Bibri and Krogstie 2017a; Böhlen and Frei 2009; Kitchin 2014; Kyriazis et al. 2014; Lee et al. 2008; Perera et al. 2014; Shepard 2011; Shin 2009; Zanella et al. 2014)—which can support sustainable urban living in various ways through intelligent service provision and decision support, will be commonplace in the near future.

3.5.2 Context Awareness and Its Feasibility in Urban Intelligence

Being of prominence and significance to ICT of the new wave of computing in the context of smart sustainable cities (Bibri and Krogstie 2016a, 2017a, b), context awareness is grounded in the idea that it becomes possible to, through the use of artificial intelligence, detect, monitor, analyze, and model situations of urban life in ways that enable a wide variety of applications and systems to adaptively and proactively take more knowledgeable actions. This relates to the prevailing idea in AmI, UbiComp, and SenComp that the environment can sense and intelligently react to contextual features of urban systems and citizens in the realm of smart sustainable cities of the future (Bibri and Krogstie 2017a, b). This constitutes also a core characteristic aspect of what is labeled "smarter cities" (Bibri and Krogstie 2017a, b). However, in contrast to the context-aware applications directed to humans (cognitive, emotional, social, and conversational features of context), where the feasibility issues are essentially linked with the inherent complexity surrounding the modeling of situations of human life (Bibri 2015a), the context-aware applications directed for urban systems are not expected to involve such feasibility issues since it is possible to model situations of urban systems as intelligent operating and organizing entities. However, these models should be sophisticated enough and well suited to include the evolution of urban phenomena under major changes. In other words, new models should focus on addressing the problems of sustainability and urbanization. Investigating approaches to context modeling (representation and reasoning techniques) constitutes a large part of a growing body of research on the use of context awareness as a technique for developing context-aware applications and systems that can adapt to and act autonomously on behalf of citizens and urban systems. ICT of the new wave of computing will enhance the quality and speed of urban models in terms of both computational capabilities and structures, as well as the scope of the evolving issues that new modeling approaches can address (Batty et al. 2012). Moreover, with the huge potential of artificial intelligence programs and machine learning and data mining techniques being under development for smart sustainable cities of the future, novel methods will emerge to address the issues related to most of the reasoning processes suggested for urban scenarios as to the complexity of generating inferences based on relatively limited and imperfect sensor data. Explicitly, new development is expected to provide ways of filling in missing data and addressing data uncertainty and vagueness using dynamic models of the very systems that these data pertains to.

3.5.3 Sensor Observations and Dynamic Urban Models

Context-aware applications and systems involve sensors to monitor or observe different contextual aspects of intelligent entities in urban environments, analyze and interpret the collected contextual data, generate inferences by reasoning against context models, and then react (and pre-act) accordingly. These processes pertain to both urban systems and information systems used by citizens. Regarding urban systems, multilevel integrated modeling is central to the endeavor of merging real-time data with traditional data across urban domains as sectional sources in a way that link real-time issue to long-term strategic planning in terms of sustainability, i.e., energy systems, transport systems, and traffic systems. However, the idea of smart sustainable cities of the future is that, based on context-aware computing, related applications and systems can be made more perceptive and responsive by becoming aware of their surroundings (monitoring or observing the urban environment in its various forms, including physical, environmental, operational, behavioral, spatiotemporal, and socioeconomic) and reacting to this awareness that can be attained by means of multiple, diverse sensors embedded throughout the urban environment that help build and maintain diverse models that represent the state of the dynamically changing and evolving urban world. Both the observed information about and the existing dynamic models for this world serve as input for the process of computational understanding, which involves the analysis and estimation of what is happening in the urban environment. The dynamic models can be viewed as interpretations of the urban environment, and thus are to be continuously improved to inform intelligent decision-making through machine reasoning about the meaning of all kinds of relevant situations taking place in that environment. Hence, they stand between the urban environment to be sensed and analyzed based on context data and the abstract notion of application actions. Dynamic models represent situations as problem and solution statements or sets of propositions expressing relationships among urban constructs which form the vocabulary of, and used to describe problems and to specify their solutions within urban sustainability domain, to draw on Bibri (2015a). They, therefore, serve as an important input together with the collected sensor data from multiple sources to context-aware applications and systems. Important to note is that new dynamic models should be developed based on what constitutes smart sustainable cities in terms of their systems, processes, and forms. They are key in context information processing associated with real-time (and sometimes offline) applications in relation to such cities. Crucially, such models must be comprehensive, consistent, flexible, robust, and have a high degree of fidelity with real-world urban phenomena.

A common use of the sensing and computing devices in smart sustainable cities of the future is to build and maintain an urban world model (see Fig. 3.2), which allows various context-aware applications and systems to be constructed and operate intelligently to catalyze and boost the process of sustainable development using such strategies as optimization, control, and management concerning urban systems as well as service efficiency and enhancement with regard to citizens.

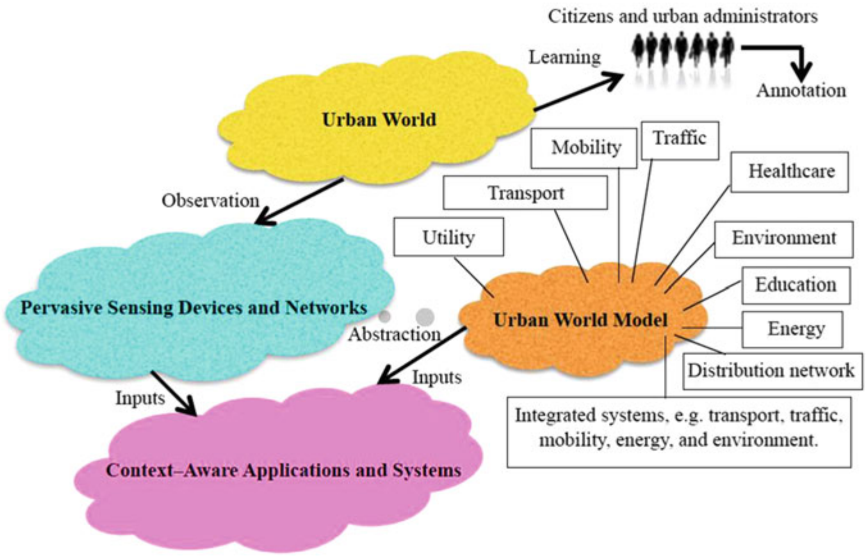

Fig. 3.2 Context awareness as an adaptive process where the smart sustainable city information systems incrementally create a model of the urban world they observe

Figure 3.2 illustrates an adaptive context awareness process where the smart sustainable city information and urban systems incrementally create the urban world they observe using sensors (and datasets). In this process, the users of such systems (citizens and urban operators/administrators) can be taken into the loop to train and detect contexts on the spot; the systems learn new situations by example, with their users as the teachers. This flexible learning scheme, which is essential to the evolution of urban models, is known as incremental learning, that is, old classes can be retrained should they have changed, and new classes can be trained with no need to retrain the ones that were already trained (see Bibri 2015a). In this way, urban contexts can be learned and recognized automatically, that is, sensor observations can be associated with human-defined context labels using machine learning and reasoning techniques.

3.5.4 Urban Context Recognition Techniques and Algorithms

3.5.4.1 Machine Learning and Hybrid Modeling in Context-Aware Computing

Context-aware computing as a prerequisite enabling technology for AmI, UbiComp, and SenComp is heralding new ways of interaction and applications in the context of smart sustainable cities. Pattern recognition algorithms in context-aware computing are under vigorous investigation in the development of smart urban environments. A multitude of such algorithms and their integration are being proposed and studied on the basis of the way in which urban contexts are operationalized, modeled, represented, and reasoned about. This can be done during a specification process whereby either concepts of context and their interrelationships are described based on urban knowledge (from city-directed disciplines) and represented in a computational format that can be used as part of reasoning processes to generate inferences, i.e., ontologies are used to represent and reason about context information, or contexts are learned and recognized automatically, i.e., machine learning techniques are used to build context models and perform further means of pattern recognition, i.e., probabilistic and statistical reasoning. While several context recognition algorithms have been applied in the area of context-aware computing, the most commonly used ones are those that are based on machine learning techniques and ontological approaches. Such techniques and approaches have been integrated into various context-aware applications. This falls under what is referred to as hybrid context modeling and reasoning approaches, which involve both knowledge representation formalisms and reasoning mechanisms. (See Bibri 2015a for examples of hybrid approaches developed in relation to various application domains). Hybrid approaches involve other methods, such as case-based methods, rule-based methods, logic programing, and database modeling techniques. The interested reader can be directed to Bibri (2015a) for a detailed overview of ontological approaches, to Bettini et al. (2010) for case-based methods, to Chen and Nugent (2009) for a short account of logical modeling and reasoning and related algorithms in terms of logical theories and representation formalisms, and to Strimpakou et al. (2006) for database modeling techniques.

Hierarchical hybrid models are assumed to bring clear advantages in terms of the set of the requirements defined for a generic context model used by context-aware applications. For example, they can provide solutions to overcome the weaknesses associated with the expressive representation and reasoning in description logic. Bettini et al. (2010) contend that there is likelihood to satisfactorily address a larger number of the identified requirements by hierarchical hybrid context model if hybrid approaches can be further extended to design such model. The authors propose a model that is intended to provide a more comprehensive solution in terms of expressiveness and integration of different forms of reasoning. In this model, the representation formalism used to represent data retrieved from a module executing some sensor data fusion technique should, in order to support the scalability requirements of context-aware services, enable the execution of efficient reasoning techniques to infer high-level context data on the basis of raw ones by, for example, executing rule-based reasoning in a restricted logic programming language. As suggested by the authors, a more expressive, ontology-based context model is desirable on top of the respective representation formalism, as it inevitably does not support a formal definition of the semantics of context descriptions. See Bibri (2015a) for an illustration of the corresponding framework and a description of its multiple layers. This framework can be adapted so to fit in with context-aware applications pertaining to smart sustainable cities.

3.5.4.2 Supervised Versus Unsupervised Methods

The concepts of supervised and unsupervised were inherited from the area of machine learning, a subfield of artificial intelligence that deals with artificial systems that are able to improve their performance overtime, in response to their experience in the world. Specifically, machine learning is the subfield of computer science that is concerned with the development of software programs that provide computer systems with the ability to learn from experiences without pursuing explicitly programmed instructions—that is, to teach themselves to grow and change when exposed to new data (Bibri 2015a). As a widely quoted, more formal definition provided by Mitchell (1997, p. 2), “A computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E.” Such improvement often involves analyzing data from the environment and making predictions about unknown variables.

Making the computer systems deployed throughout urban environments able to compute, communicate, and share data does not make them intelligent; rather, the key and challenge to really equipping these systems with intelligence and augment such environments with it lies in the way the systems learn and keep up to date with the needs and requirements of citizens and urban system respectively by themselves in the context of sustainability. In fundamentally operational terms, this description resonates with the idea that computer systems can think, a technological feature that underlies the prevalent ICT visions of pervasive computing, most notably UbiComp, AmI, and SenComp in terms of context-aware applications. However, it is computationally unfeasible to build models for all sorts of situations of urban life concerning context-aware applications. The underlying assumption is that training sets are finite, urban life situations are dynamic, and behavioral patterns of urban systems are uncertain, and so on, adding to the limited routinely generated sensor data in the context of real-time urban functioning. Besides, "notwithstanding the huge potential of machine learning techniques, the underlying probability theory usually does not yield assurances of the performance of algorithms; rather, probabilistic (and statistical) reasoning limits to the performance are quite common. This relates to computational learning theory, a branch of theoretical computer science that is concerned with the computational analysis of machine learning algorithms and their performance in relation to different application domains" (Bibri 2015a, p. 172). In relation to context-aware applications, machine learning involves a wide variety of algorithms which can be classified into different categories based on the following methods (Bibri 2015a):

- Supervised and unsupervised learning (explained below);
- Semi-supervised learning (combines both labeled and unlabeled examples to generate an appropriate classifier);
- Transductive inference (attempts to predict new outputs on specific test cases from observed training cases);
- Learning to learn (learns its own inductive bias based on previous experience); and
- Reinforcement learning (executes actions which trigger the observable state of a dynamic environment to change, and attempts to gather information about how the environment reacts to actions as well as to synthesize a sequence of actions that maximizes some notion of cumulative reward).

Indeed, issues of agency and cognition in terms of how an intelligent agent use learned knowledge to reason and act in its environment are characteristic to machine learning.

3.5.4.3 Context Recognition Techniques and Algorithms

Context recognition algorithms based on supervised and unsupervised learning methods primarily use probabilistic and statistical reasoning. Supervised learning requires the use of labeled data on which an algorithm is trained, and training sets are called labeled data because the value for the class label is known. Following training the algorithm can classify unknown and future data. Thus, the basic idea of supervised learning is to classify data in formal categories that an algorithm is trained to recognize. In this sense, the machine learning process examines a set of atomic contexts which have been pre-assigned to categories and makes inductive abstractions based on these data that assist in the process of classifying unknown and future atomic contexts into high-level contexts. Supervised learning algorithms require an important training period during which several examples of each context and related concepts are collected and analyzed. The quality of training influences the outcome of the classification critically. And the granularity of the learned context concepts is influenced by the availability and nature of the low-level contextual data from sensors (Bettini et al. 2010). In all, supervised learning algorithms enable context-aware applications and systems to keep a trace of their previous observed experiences in the form of trained classes of context and employ them to dynamically learn the parameters of the stochastic context models (a pattern that may be analyzed statistically but not predicted precisely). This enables them to generate predictive models based on the observed agents' context profiles. The general process using a supervised learning algorithm for context recognition encompasses several steps, namely, borrowing Chen and Nugent's (2009) terminology:

(1) To acquire sensor data representative of relevant context features/attributes pertaining to citizens or urban systems, including related labeled annotations.
(2) To determine the input data features and their representation.
(3) To aggregate data from multiple data sources and transform them into the application-dependent features, e.g., through data fusion, noise elimination, dimension reduction, and data normalization.
(4) To divide the data into a training set and a test set.
(5) To train the recognition algorithm on the training set.
(6) To test the classification performance of the trained algorithm on the test set.
(7) To apply the algorithm in the context of context recognition. It is common to repeat steps (4–7) with different partitioning of the training and test sets in order to achieve better generalization with the recognition models.

There are a wide range of algorithms and models for supervised learning and context recognition. In the area of context recognition, the basic idea of classification is to determine different context labels on the basis of a set of context categories (training examples) learned from the real world as models. The algorithm is presented with a set of inputs and their desired outputs, e.g., association of sensor data with real-world contexts, and the goal is to learn a general rule that maps inputs (e.g., sensor data) to outputs (context labels), so that the algorithm can map new sensor data into one of these context labels. The quality of classification, how well a classifier performs, is inextricably linked to the richness of the learning experience of the algorithm, and also depends critically on the features of the contextual data to be classified. Building new models, training new classes, during the analysis of the collected sensor data is important for making future inductive abstractions in terms of classifying unknown and future contextual data (i.e., performance) through gaining experience. Classification of contexts is done using a classifier that is learned from a comprehensive training set of annotated context examples. Classifiers represent tasks entailing the use of pattern matching to determine the best match between the features extracted from sensor data and a context description. This is about classifying sensor cues into a known category and storing general patterns of context. There are various supervised learning classifiers, and they vary in terms of performance, which depends on the application domain to which they can be applied. For example, binary decision tree uses a decision tree as a predictive model which maps sensor observations to inferences about the context's target value. Support Vector Machine (SVM) builds a model that predicts into which of two categories a new example falls, assuming that each training example is marked as belonging to one of these two categories. Other classifiers include neural network, k–nearest neighbor, dynamic and naive Bayes, and Hidden Markov Models (HMMs). They have been applied in a wide variety of context awareness domains within both laboratory-based as well as real-world environments (see Bibri (2015a) for a set of selected examples). Important to note is that neither one classifier is superior to another, nor is there a single classifier that works best for all on all given problems. It follows that to determine a suitable classifier for a given problem domain is linked to the complexity and nature of that problem domain. Still, among the supervised learning algorithms, HMMs and Bayes networks are thus far the most commonly applied methods in the area of context recognition. While both of them have been shown to be successful in context-aware computing, they are both very complex and require lots of a large amount of labeled training and test data. This is, in fact, the main disadvantages of supervised learning algorithms in the case of probabilistic methods, adding to the fact that it could be computationally costly to learn each context in a probabilistic model for an infinite richness or large diversity of contexts in real-world application scenarios (see Chen and Nugent 2009). Moreover, given that context-aware applications usually incorporate different contextual features that should be combined in the inference of a particular dimension of context, adding to the fact that one feature may involve different types of sensor data, the repetitive diversification of the partitioning of the training and test sets may not lead to the desired outcome with regard to the generalization with the context recognition models. This has implication for the accuracy of the estimation of context, that is, the classification of dynamic contextual data into relevant context labels. Machine learning methods in the case of probabilistic methods "choose a trade-off between generalization and specification when acquiring concepts from sensor data recordings, which does not always meet the correct semantics, hence resulting in wrong detections of situations" (Bettini et al. 2010, p. 11). A core objective of a learning algorithm is to generalize from its experience whereby generalization denotes the ability of a learning mechanism to perform accurately on not previously seen context examples after having experienced a learning data set—the combination of context patterns and their class labels. While this is a decision that should be made, the resulting context models are often ad hoc and not reusable. In fact, supervised learning algorithms inherently suffer from several limitations, namely scalability, data scarcity, inflexibility, ad hoc static models; these methods “should tackle technical challenges in terms of their robustness to real-world conditions and real-time performance” (Chen and Nugent 2009). New research endeavors should focus on creating alternative theories based on new discoveries in human-directed sciences in terms of developing less complicated, computationally elegant, and, more importantly, effective and robust algorithms with wider applicability, irrespective of the application domain.

Distinct from supervised learning, unsupervised learning tries to directly build recognition models from unlabeled data. With having no labels, the learning algorithm is left on its own to group similar inputs or density estimates that can be visualized effectively (Bishop 2006). Thus, unsupervised learning provides context-aware applications with the ability to find context patterns in cues as abstraction from raw sensor data—i.e., features extracted from the data stream of multiple, diverse sensors. Probabilistic algorithms can be used for finding explanations for streams of data, helping recognition systems to analyze processes that occur over time (Russell and Norvig 1995). The basic idea of unsupervised learning algorithm is to manually assign a probability to each possible context and to use a pre-defined stochastic model to update these likelihoods on the basis of both new sensor readings and the known state of the system (see Chen and Nugent 2009). The general process of unsupervised learning algorithms for context recognition includes the following steps Chen and Nugent (2009, p. 414):

(1) To acquire unlabeled sensor data.
(2) To aggregate and transform the sensor data into features.
(3) To model the data using either density estimation (to estimate the properties of the underlying probability density) or clustering methods (to discover groups of similar examples to create learning models).

There exist several algorithms for unsupervised learning that are based on probabilistic reasoning, such as Bayes networks, graphical models, multiple eigen spaces, and different variants of HMMs. Further, unsupervised learning probabilistic methods are capable of handling the uncertainty and incompleteness of sensor data. Probabilities can be used to serve various purposes in this regard, such as modeling uncertainty, reasoning on uncertainty, and capturing domain heuristics (see, e.g., Bettini et al. 2010; Chen and Nuget 2009). However, unsupervised learning probabilistic methods are usually static and highly context-dependent, adding to their limitation as to the assignment of the handcrafted probabilistic parameters (e.g., modeling uncertainty, capturing heuristics) for the computation of the context likelihood (see Chen and Nugent 2009). Indeed, they seem to be less applied than supervised learning in the domain of context recognition.

3.5.4.4 Conceptual Context Models and a Framework for Integrating the Key Ingredients

As high-level abstractions of contexts can be semantically abstracted from contextual cues extracted from low-level context data obtained from physical sensors, human knowledge, and interpretation of the urban world must be formally conceptualized and modeled according to certain formalisms. In smart sustainable cities, conceptual context models are concerned with what constitutes various types of contexts and their conceptual structures depending on the application domain. While the semantics of what constitutes "context" has been widely discussed in the literature and defining what constitutes context information has been studied extensively in relation to humans (e.g., Bibri 2015a), little, if no, attention has been given to what constitutes context information in relation to urban systems (energy, traffic, transport, etc.). This is a fertile research area in the realm of smart sustainable cities. Generally, context information in the urban domain refers to the representation of the situation of an entity (energy system in a building, a traffic system in a district, a transport system in an urban area characterized by mixed land use and density, etc.) in some computer system run by, for example, an urban department, where a set of contextual features are of interest to a provider of operational functioning services for assessing the timeliness and context-dependent aspects of the system behavior. Works that can identify qualitative features of urban system context information remain scant. And those related to citizens are numerous and diverse (see Bibri (2015a) for a detailed survey). However, most of the latter class of works does not provide formal representations of the proposed models.

However, one of the challenges in smart sustainable cities is to provide frameworks that cover the class of context-aware applications that exhibit computational understanding and intelligent behavior in relation to sustainability performance. Here computational understanding entails performing the analysis and interpretation of context data, including reasoning about such data, and estimating what is happening in the urban environment (high-level abstractions of context pertaining to various urban systems), a process for which input is observed information about the situations of urban systems over time (i.e., urban monitoring) and dynamic models for the spatial, spatiotemporal, physical, infrastructural, environmental, and socioeconomic processes of smart sustainable cities. Note that different types of models are needed. Intelligent behavior entails context-aware applications coming up with and firing situation-dependent actions that provide support for different aspects of sustainability. With the above in mind, a basic framework can be suggested, which combines different models and methods, as illustrated in Fig. 3.3.

Figure 3.3 shows a basic framework which combines urban state and history models, environment state and history models, dynamic process models (about urban functioning), dynamic environment process models, ontologies and knowledge from city-related disciplines (including urban sustainability), and analysis methods on the basis of such models, such as spatial analysis, spatiotemporal analysis, environmental analysis, behavioral analysis, and so on. As a template for

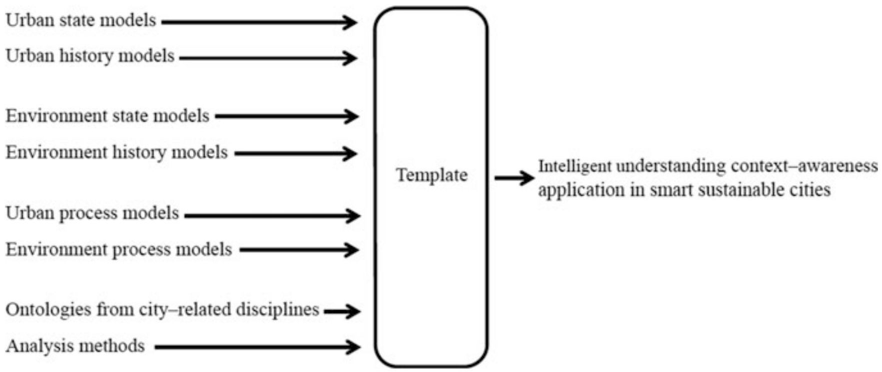

Fig. 3.3 A framework for integrating the key ingredients

the class of context-aware applications showing computational understanding and intelligent behavior, the framework can encompass slots where the content of applications specific to various urban systems together with the generic operative methods can be filled in order to obtain an executable design for a working application. Accordingly, context-aware applications can show advanced computational understanding of the urban environment and react from this understanding in a knowledgeable manner through intelligent decision-making for improving different aspects of sustainability through optimization, control, management, and planning of urban systems.

3.5.4.5 A Basic Multilayered Architecture of Context Information Processing

Researchers from different application domains have investigated context awareness for the past two decades or so by developing a diversity of architectures (see Bibri (2015a) for an overview). Context awareness involves a wide range of architectures that basically aim to provide the appropriate infrastructures for context-aware applications pertaining to diverse application domains. Context-aware applications are based on a multilayered architecture, as shown in Fig. 3.4. Here the focus is on urban systems.

Layer 1—Physical sensors. Signals in the urban environment are detected from multiple sources using sensors of many types. This sensor layer is usually defined by open-ended (unrestricted) collection of sensors embedded in urban systems and spread in their surrounding environment. The data supplied by sensors, irrespective of the application domain (traffic, energy, transport, mobility, etc.), are usually very different, ranging from slow sensors to fast and complex sensors that provide larger volume and higher velocity of data.

Layer 2—Context data processing. This layer is dedicated to aggregate, fuse, organize, and propagate contextual data. At this stage, signal processing and

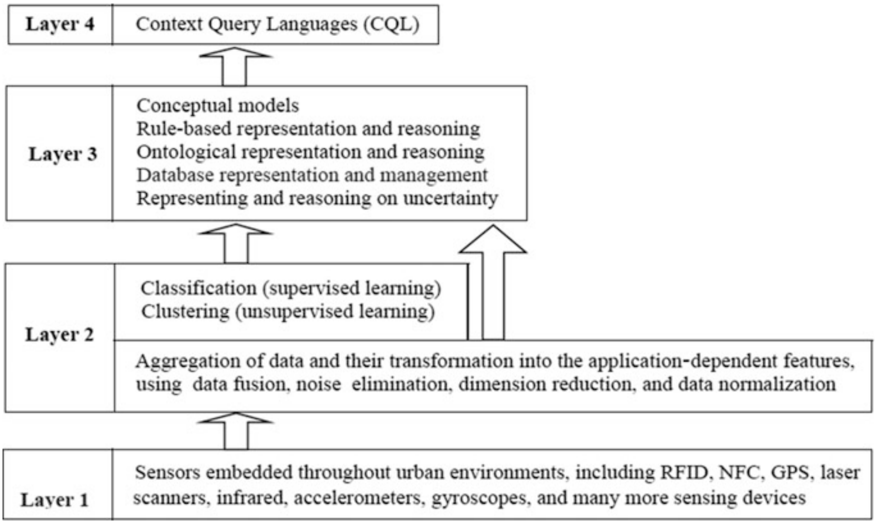

Fig. 3.4 A basic multilayered architecture underlying context information processing. *Source* Adapted from Bibri (2015a)

machine learning techniques (preprocessing, analysis, and pattern recognition) are used to recognize situations of urban systems from sensor signals and labeled annotations in the case of classification, for example. The recognition can also occur through mapping sensor readings to matching properties described in ontologies of particular urban domains in the case of hybrid models, and using these ontologies to aggregate and fuse sensor observations to generate situations of urban systems. Which recognition approach to espouse is determined by how context is modeled and thus encoded and reasoned about. However, as contextual data need at this stage to be organized in the form of information, this layer introduces abstractions of real-world situations.

Layer 3—Context representation and reasoning. As the core of context modeling, this layer involves the application of representation and reasoning techniques, which usually entail an integration of different modeling approaches for an effective outcome as to the estimation of the situation of urban systems. Indeed, this hybrid method allows to address issues such as uncertainty, incompleteness, and vagueness associated with contextual information.

Layer 4—Application action. At this layer, actions are fired based on the generated inferences. Specifically, decisions are taken as to what actions are to be executed on the basis of high-level abstractions of situations produced through reasoning processes. The type of actions to be performed is typically dependent on the application domain. For example, the actions taken at the application level can be oriented toward supporting energy efficiency, traffic congestion reduction, transport management, and so on. Furthermore, there is a variety of context query languages that can be used by context-aware applications, as there is no specific requirement in context awareness architectures with respect to which query languages to use. However, the selection of the query language is contingent upon the applied modeling approaches in terms of representation and reasoning techniques. "The meaning of the queries must be well-specified because in the implementation the queries are mapped to the representations used in layer 3. An important role of the middle layer and the query language is to eliminate direct linking of the context providing components to context consuming components… Thus, the query language should support querying a context value regardless of its source… It should be noted that since the CQL acts as a facade for the applications to the underlying context representation, the context information requirements of the applications are imposed as much on the query language as on the context representation and context sources" (Perttunen et al. 2009, p. 2).

Figure 3.4 illustrates four layers of context information processing. The architecture also includes examples of existing techniques and methods that can be used in context-aware applications, depending on the application domain and its complexity and scale.

However, while some advanced design alternatives for context awareness architectures are being deployed in smart sustainable cities, it will take some time before standard, interoperable context information modeling and management become a reality.

3.6 Conclusions

Big data analytics and context-aware computing are rapidly growing areas of ICT that are becoming even more important to smart sustainable cities with respect to their operational functioning and planning to improve their contribution to the goals of sustainable development. These concepts were crystallized into realist notions in the domain of sustainable urban planning not too long ago—until UbiComp, AmI, the IoT, and SenComp as the most prevalent ICT visions of pervasive computing have become achievable and deployable paradigms and also matured thanks to the recent advances in sensor technologies, data processing platforms, cloud computing and middleware infrastructures, and wireless communication networks. This major technological transition is drastically changing how smart sustainable cities can be monitored, understood, analyzed, and planned to advance sustainability. Accordingly, big data analytics and context-aware computing are opening unique windows of opportunity for enabling such cities to leverage their informational landscape by developing, deploying, and implementing a variety of advanced applications to enhance their operational functioning, planning, and design in line with the vision of sustainability.

The aim of this chapter was to review and synthesize the relevant literature with the objective of identifying and distilling the core enabling technologies of big data analytics and context-aware computing as ecosystems in relevance to smart sustainable cities, as well as to illustrate the key computational and analytical techniques and processes associated with the functioning of such ecosystems. The key contribution of this chapter lies in developing, elucidating, and evaluating a number of relevant frameworks pertaining to big data analytics and context-aware computing in the context of smart sustainable cities by bringing together research at a more conceptual, analytical, and overarching level to stimulate new ways of investigating their role in advancing urban sustainability. The proposed frameworks, which can be replicated and tested in empirical research, will add additional depth and rigor to studies in the field. Big data analytics and context-aware computing share basically the same core enabling technologies in the realm of smart sustainable cities, especially their effects overlap in many aspects with regard to advancing the process of sustainable development. The underlying enabling technologies and related key computational and analytical techniques and processes consist of the following:

- Data collection and preprocessing, e.g., data sensing methods and signal processing techniques;
- Data repositories or storage facilities, e.g., database and data warehouse servers;
- Data processing, e.g., data analytic systems, cloud computing models, middleware architectures, including software tools and database systems;
- Analysis techniques and algorithms, e.g., data mining, machine learning, statistics, and database query and related computational mechanisms;
- Wireless network technologies, e.g., the satellite-enabled GPS, mobile phone, LPWAN, and Wi-Fi networks, for collecting and coordinating data in terms of the data themselves and how that data are stored and made accessible; and
- Data visualization for representing and displaying useful and context knowledge in understandable formats for human interpretation.

Adding to the above components are privacy and security mechanisms, open standards and standard rules, as well as conceptual frameworks (data mining process, context recognition process, context information processing, etc.) and related methods (supervised and unsupervised learning).

Furthermore, the availability of the various permutations of the core enabling technologies underlying big data analytics and context-aware computing is justified by the varied technical details of the application domains pertaining to smart sustainable cities in terms of their complexity, scale, requirement, and objective. Regardless, to facilitate an effective functioning of big data and context-aware applications, it is important to ensure a seamless amalgamation of their core enabling technologies. This is of equal importance to better understand, monitor, analyze, and plan smart sustainable cities for the purpose of catalyzing and boosting the process of sustainable development toward achieving the long-term goals of sustainability.

The emerging ability to use big data and context-aware techniques and methods for advancing sustainability promises to revolutionize various urban domains. The key applications enabled by big data analytics and context-aware computing include transport, mobility, traffic lights and signals, energy systems, power grid, environment, buildings, public safety and civil security, planning and design, healthcare, education and learning, the quality of life, and urban infrastructures and facilities monitoring and management. Besides all the benefits, the large-scale deployment and amalgamation of big data analytics and context-aware computing as advanced forms of ICT is beset with several challenges due to the massive size, diverse nature, and fast-changing pace of big data and to the constraints of system engineering, design, and modeling of context awareness.

In all, the use of big data analytics and context-aware computing entails that smart sustainable cities take the form of constellations of architectures, platforms, applications, and computational and data analytics capabilities connected through wirelessly ad hoc and mobile networks with a modicum of intelligence across several spatial scales, which provide and coordinate continuous data regarding the physical, infrastructural, spatial, spatiotemporal, operational, functional, and socioeconomic forms of such cities. We argue that big data analytics and context-aware computing are prerequisite technologies for the functioning of smart sustainable cities of the future, as their effects reinforce one another as to their efforts for bringing a whole new dimension to the operating and organizing processes of urban life in terms of employing a wide variety of smart and data-driven applications for advancing sustainability.

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Chapter 4
Data Science for Urban Sustainability: Data Mining and Data-Analytic Thinking in the Next Wave of City Analytics

Abstract As a research direction, big data analytics has recently attracted scholars and scientists from diverse disciplines, as well as practitioners from a variety of professional fields, given their prominence in various urban domains, especially urban design and planning, transportation engineering, mobility, energy, public health, and socioeconomic forecasting. Indeed, there has recently been much enthusiasm about the immense possibilities created by the data deluge and its new sources to better operate, manage, and plan cities to improve their contribution to the goals of sustainable development as a result of thinking about and understanding sustainability problems in a data-analytic fashion. This data deluge is increasingly enriching and reshaping our experiences of how such cities can be advanced. Big data analytics is indeed offering many new opportunities for well-informed decision-making and enhanced insights with respect to our knowledge of how fast and best to improve urban sustainability. This unprecedented shift has been brought up by data science, an interdisciplinary field which involves scientific systems, processes, and methods used to extract useful knowledge from data in structured or unstructured forms. Data mining and knowledge discovery in databases as processes are by far the most widely used techniques for extracting useful knowledge from colossal datasets for enhanced decision-making and insights in relation predominantly to business intelligence. However, in city-related academic and scientific research, it is argued that “small data” studies—questionnaire surveys, focus groups, case studies, participatory observations, audits, interviews, content analyses, and ethnographies—are associated with high cost, infrequent periodicity, quick obsolescence, reflexivity, incompleteness, and inaccuracy, i.e., capture a relatively limited sample of data that are tightly focused, time and space specific, restricted in scope and scale, and relatively expensive to generate and analyze, to provide additional depth and insight with respect to urban phenomena. Accordingly, much of our knowledge of urban sustainability has been gleaned from studies that are characterized by data scarcity. The potential of big data lies in transforming the knowledge of smart sustainable cities through the creation of a data deluge that seeks to provide much more sophisticated, wider scale, finer grained, real-time understanding, and control of various aspects of urbanity. Therefore, this chapter aims to synthesize, illustrate, and discuss a systematic

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framework for urban (sustainability) analytics based on Cross-Industry Standard Process for Data Mining (CRISP-DM) in response to the emerging wave of city analytics in the context of smart sustainable cities. This framework, which can be tested and used in empirical applications in the city domain, has an innovative potential to advance urban analytics by providing a novel way of thinking data-analytically about urban sustainability problems. It provides fertile insights into how to conduct "big data" studies in the field of urban sustainability. The intent is to enable well-informed or knowledge-driven decision-making and enhanced insights in relation to diverse urban domains with regard to operations, functions, strategies, designs, practices, and policies for increasing the contribution of smart sustainable cities to the goals of sustainable development. This chapter can serve to bring together city analysts, data scientists, urban planners and scholars, and ICT experts on common ground in their endeavor to transform and advance the knowledge of smart sustainable cities in terms of sustainability.

Keywords Smart sustainable cities · Big data analytics · Data mining
Knowledge discovery · Techniques and algorithms · Urban analytics
Urban sustainability · Databases · Big data studies · Decision-making

4.1 Introduction

Currently, more than half (54%), and by 2050 more than two-thirds (66%), of the world's population is expected to be urbanized or live in cities (United Nations 2015a). Every second, the global urban population increases by 2 people, and soon will exceed 3.9 billion people. This implies an unprecedented series of significant challenges for city governments associated with environmental, economic, and social sustainability due to the issues engendered by urban growth in terms of intensive energy consumption, endemic congestion, saturated transport networks, air and water pollution, toxic waste disposal, resource depletion, environmental degradation, sprawl, inadequate decision-making and planning systems, inefficient management of urban infrastructures and facilities, poor housing and working conditions, social inequality and vulnerability, public health decrease, and so on (Bibri and Krogstie 2017a). Urbanization generates many problems of control in the management of resources and land use (Lenormand and Ramasco 2016). In short, the multidimensional effects of urban unsustainability are most likely to exacerbate with urbanization. In other words, urbanization will aggravate the unsustainability of cities. Indeed, urbanization as a dynamic clustering of people, buildings, and resources puts an enormous strain on the limited urban resources and affects the resilience to the growing demands on them, and urban management and governance face ever-mounting challenges. To disentangle these intractable problems requires evidently unprecedented shifts in urban thinking and planning—i.e., newfangled ways founded on more innovative solutions and sophisticated approaches with respect to how cities can be conceived of, managed, and developed (Bibri and Krogstie 2017a).

This challenges the cities' institutions to develop smart infrastructures and services for mobility, health care, education, energy, traffic, transport, and governance, and push enterprises to invest into sustainable economic development. Due to a wide variety of human sensor and other sensors that are integrated into public transport, infrastructure, facilities, buildings, and streets, coupled with open data from city government and councils, a plenitude of data exists—deluge. Making cities "smarter" has the potential to provide a solution for handling more efficiently new sources of data, to gain a better understanding of urban dynamic, and to search for more sustainable living conditions (Lenormand and Ramasco 2016). In this regard, big data innovations can provide integrated information intelligence for enhancing urban operational functioning, management, planning, design, socioeconomic forecasting, and policy development on the basis of participatory, poly-centric, and digital models and processes of governance. Besides, the planning and development of cities as complex systems and dynamically changing environments in terms of how they function and can be managed and developed require smart solutions and methods. The tremendous and multifaceted potential of smart urban approaches has been under investigation by the United Nations (2015a), through their study on "Big Data and the 2030 Agenda for Sustainable Development."

The data-intensive scientific development as a new paradigm, which has materialized as a result of the recent advances in data science systems, processes, and methods, is instigating a drastic shift in city-related academic and scientific disciplines, including urban planning, urban design, sustainability science, sustainable development engineering, urban computing, applied urban science, and environmental sciences. Adding to this is the way such disciplines may potentially be combined into new interdisciplinary or transdisciplinary fields. Turing award winner Jim Gray envisioned data science as the new paradigm of science, and asserted that everything about science is changing because of the impact of ICT and the data deluge (Bell et al. 2009). The Petabyte Age is upon us, and the data deluge makes the scientific approach—hypothesize, model, test—obsolete. The way science has worked for hundreds of years is that theoretical models of how the world works as systems visualized in the minds of scientists are tested, and then experiments confirm or falsify them. Data-intensive scientific discovery is the fourth paradigm of scientific development, with the first paradigm being where science used empirical methods thousands of years ago, the second paradigm where science became a theoretical field a few hundred years ago, a process of creating and testing hypotheses; the third paradigm where science relied on calculation, conducting simulation and verification by computation in recent decades; and the fourth (current) paradigm is where science involves the exploration and mining of scientific data and using data mining techniques to unify theory, simulation, and experimental verification (Bell et al. 2009). This is increasingly gaining a foothold in many academic and scientific research fields, taking over the process of creating and testing hypotheses predominately. Here, the use of data mining is seen as an important and effective way to, in addition to conducting scientific exploration and discovery based on big data, solve complex problems within a wide number and variety of domains, especially sustainability. As foundational topics in data science, data manipulation, data analysis, and data communication are becoming increasingly of prime focus in understanding and probing complex urban problems and phenomena, using techniques and methods drawn from such diverse fields as information science, computer science, complexity science, and formal science, in particular from the subfields of machine learning, data mining, statistical analysis, mathematical modeling, artificial intelligence, database management, pattern recognition, and data visualization. By mining the big data of smart sustainable cities, it is possible to explore and discover laws and principles of sustainable development pertaining to environmental and socioeconomic aspects of the city. This development will allow an inference of the city stakeholders' responses to products, services, operations, and functions, as well as to strategies, designs, policies, and other practices.

Data science has brought a new perspective on the way urban problems can be conceived of, understood, and tackled, using a range of big data analytics techniques to extract useful knowledge from large masses of urban data for enhancing decision-making and providing valuable insights in relation to urban operations, functions, designs, strategies, practices, and policies. One key application area of data science and related big data analytics is sustainable urban planning. There has recently been much focus on the immense possibilities created by new and more extensive sources of urban data to better monitor, understand, analyze, evaluate, and plan smart sustainable cities to improve their contribution to the goals of sustainable development. The use of big data analytics as a set of advanced techniques offers the prospect of cities in which natural resources can be managed sustainably and efficiently by means of data-driven methods to enhance societal and economic outcomes. This epitomizes what smart sustainable cities of the future entail and aim for: a set of transformative, innovative urban processes and approaches that amalgamate technological capabilities and strategic decision-making to advance the functioning, management, and planning of urban systems on the basis of a quest for promoting the health of individual citizens, communities, and natural ecosystems; conserving resources; and fostering economic development. Data-analytic and sustainable thinking as an integrated approach into smart sustainable city development connects the best strands of data science technologies and sustainable practices. In fact, smart sustainable cities as a techno-urban innovation have been enabled by the embeddedness of advanced data sensing, information processing, modeling, and simulation technologies into urban systems as to the underlying operations, functions, designs, services, and policies for the purpose of addressing the challenge of sustainability (Bibri and Krogstie 2016). The prospect of developing smart sustainable cities based on big data analytics is fast becoming the new reality (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri 2018a, b; Khan et al. 2015; Kitchin 2014).

Urban data deluge results from the increasing availability of the data being generated in continuous streams and on daily basis in the urban environment. Within smart sustainable cities, urbanites, processes, systems, structures, activities, networks, facilities, services, spaces, and objects all contribute to generating huge amounts of data involving heterogeneous and distributed sources. There is a phenomenal growth in data production across the world. The digital data are projected to grow from 2.7 Zettabytes to 35 Zettabytes by the year 2020 (Malik 2013; Zikopoulos et al. 2012). Manyika et al. (2011) projected a growth of 40% in data generated globally per year. It is estimated that more data are being produced every 2 days at present than in all of history prior to 2003 (Smolan and Erwitt 2012, cited in Kitchin 2014). Such explosive growth in data is due to a number of different enabling and driving technologies, infrastructures, techniques, and processes as new developments in ICT of pervasive computing, and their rapid embedding into everyday practices and spaces, enabling the accessing and sharing of data, but are also the means by which much big data are generated (Kitchin 2014). Accordingly, the urban data being generated will in principle remain a continuing stream, and thus the datasets across all urban domains will proliferate. These data are considered to be the most scalable and synergic asset or resource for smart sustainable cities. The role of big data processing technologies lies in collecting, storing, processing, analyzing, and interpreting large masses of data on every urban system and domain to discover useful knowledge and employ it to enhance decision-making and insights. The value of this knowledge lies in improving physical forms, infrastructures, resources, networks, facilities, and services by developing urban intelligence functions for automating and supporting decisions pertaining to control, automation, optimization, management, and (short-term and long-term) planning for the purpose of improving the contribution of smart sustainable cities to the goals of sustainable development. Therefore, big data constitute the fundamental ingredient for the next wave of urban sustainability analytics.

Urban analytics involves the application of various techniques based on data science fundamental concepts—i.e., data-analytic thinking and the principles of extracting useful knowledge from data—as an integral part of what is labeled "big data" studies. Data mining as one of these techniques provides some of the clearest illustrations of the principles of data science. Indeed, it is the most widely used technique in the urban domain, and presents a tremendous challenge due to the interdisciplinary and transdisciplinary nature of urban data. This pertains to all urban domains as application areas in the context of sustainability. Data mining as a process of extracting useful knowledge from urban data to use it to make important sustainability decisions in the context of smart sustainable cities is an essential step, and thus used exclusively for the discovery stage, of the process of knowledge discovery in databases. However, over the last 15 years or so, research within the area of data mining and knowledge discovery processes has been mainly active in such areas as banking, customer relationship management, targeted marketing, fraud detection, finance, retail, manufacturing, telecommunication, medicine and healthcare, media, and so on. Accordingly, there is a paucity of research on this topic in relation to the domain of urban sustainability. In particular, while big data analytics has recently become of focus in the context of smart cities (Al Nuaimi et al. 2015; Batty 2013; Batty et al. 2012; Khan et al. 2015; Kitchin 2014) as well as smart sustainable cities (Bibri 2018a; Bibri and Krogstie 2017b, c), research on the next wave of urban analytics based on data mining in the realm of academic and scientific research remains scant. Especially, in city-related research, it is argued that "small data" studies—questionnaire surveys, focus groups, case studies, participatory observations, audits, interviews, content analyses, and ethnographies—are associated with high cost, infrequent periodicity, quick obsolescence, bias, incompleteness, and inaccuracy, i.e., capture a relatively limited sample of data that are tightly focused, time and space specific, restricted in scope and scale, and relatively expensive to generate and analyze, to provide additional depth and insight with respect to urban phenomena. In view of that, much of our knowledge of urban sustainability has been gleaned from studies that are characterized by data scarcity.

This chapter is about thinking data-analytically about urban sustainability problems, which is aided by conceptual frameworks as processes with well-defined stages to help structure and systematize urban data-analytic thinking. Specifically, it aims to synthesize, illustrate, and discuss a systematic framework for urban (sustainability) analytics based on cross–industry standard process for data mining in response to the emerging wave of city analytics in the context of smart sustainable cities. The main motivation for this endeavor is to put forward new approaches into conducting urban analytics for enhancing sustainability performance.

The remainder of this chapter is structured as follows. In Sect. 4.2, we introduce, describe, and discuss relevant theoretical constructs. Section 4.3 provides a survey of related work, covering big data analytics and data mining, data processing platforms, big data for urban analytics, and 'big data' studies: academic and scientific research. In Sect. 4.4, we introduce and discuss a set of canonical data mining and knowledge discovery tasks prior to presenting the related processes. Section 4.5 presents, explains, and discusses the process of data mining, with a particular focus on data-analytic solutions to urban sustainability problems. Section 4.6 provides a set of relevant data mining applications for urban sustainability analytics. In Sect. 4.7, we suggest some ways of answering examples of urban sustainability questions using different big data analytics techniques. Section 4.8 addresses the process of knowledge discovery in databases and several related issues. In Sect. 4.9, we highlight the role of human mobility data in the next wave of urban sustainability analytics while focusing on mobility knowledge discovery and its use in relation to sustainable urban forms, as well as new systems for mobility behavior discovery in relation to sustainability. This chapter ends, in Sect. 4.10, with concluding remarks and some reflections and thoughts.

4.2 Theoretical Background

4.2.1 Data Science Fundamentals, Data Mining, and Urban Sustainability Problems

Data science is a flourishing field, and its particular concerns are relatively new and its general principles are just materializing. Its ultimate goal is to enhance decision-making pertaining to a large number and variety of domains through the practice of basing decisions on the analysis of data—data-driven decision-making (DDD). Yet, data science requires a careful thinking about what kind of available data might be used and how these data can be used depending on the application domain, specifically in terms of the problem that is to be tackled. It assumes access to and utilization of large masses of data, and often benefits from sophisticated data engineering facilitated by data processing and other software technologies being in use within a wide variety of organizations and institutions. In the context of smart sustainable cities, data science involves principles, processes, and techniques incorporated in cutting-edge technologies distributed across diverse urban entities for understanding and analyzing urban problems and phenomena in relation to environmental, social, and economic sustainability via the automated analysis of urban data, coupled with specialized knowledge, creativity, and common sense of data scientists. Accordingly, data-science-oriented analytic thinking enables one to evaluate urban sustainability proposals for data mining projects in smart sustainable cities. If a planner, strategist, or expert proposes to improve a particular energy, traffic, environment, or healthcare application by extracting knowledge from urban data, it is crucial for the data scientist (or urban analyst) to be able to assess the proposal systematically and decide whether and why it is sound or flawed. This concerns identifying obvious weak spots, unrealistic assumptions, and unconnected and missing pieces rather than determining whether it will actually succeed.

The fundamentals of data science as a set of unified concepts, principles, and techniques incorporated in data science technologies underlie big data analytics techniques—e.g., data mining as a process of extracting useful knowledge from data for enhanced decision-making and insights. In organizing thinking and analysis, these fundamentals make it possible to deeply understand data science approaches and processes instead of focusing in depth on the wide range of specific data mining algorithms (Provost and Fawcett 2013). Compared to other big data analytics techniques, coupled with the fact that data science is of wider application than the use of data mining, data mining algorithms provide the most explicit illustrations of data science fundamentals, which differ from, and are complementary to, statistics and database querying. However, in the context of smart sustainable cities, it has become important to foster the ability to approach urban sustainability problems “data-analytically,” as well as to assess how urban data can improve sustainability performance in relation to diverse urban domains (e.g., Al Nuaimi et al. 2015; Bibri 2015; Bibri and Krogstie 2017a, b). This implies that the knowledge extracted from large bodies of urban data is assumed to be in the form of nontrivial, actionable models. This entails applying a set of fundamental concepts that facilitate careful urban data-analytic thinking, understanding data mining techniques and data science applications in relation to sustainability dimensions, and developing relevant frameworks for structuring urban thinking about data analytics (sustainability) problems so that it can be done systematically. Drawn from many fields concerned with data analytics in connection with the urban domain, among the fundamental concepts of data science include, to draw on Provost and Fawcett (2013), the following:

- Extracting useful knowledge from large masses of urban data to solve urban sustainability problems (physical, environmental, social, and economic) related to diverse urban domains, which can be treated systematically by following a set of reasonably well-defined stages, i.e., several codifications of data mining process, most notably the Cross Industry Standard Process for Data Mining (CRISP-DM) (see Bibri (2015) for a detailed account with illustrative examples). This process provides a framework to structure urban thinking about data analytics problems related to different dimensions of sustainability, as in smart sustainable urban planning practice, it is important to devise analytical solutions based on careful analysis and evaluation of the relevant problems using high-powered analytical and evaluative tools, as well as creativity, common sense, and specialized knowledge, to reiterate. Therefore, structured thinking about urban data analytics is of significance to supporting decision-making processes concerning different aspects of sustainability within almost all urban domains.
- Urban ICT can be employed to discover informative descriptive attributes of entities (citizens, transport/mobility systems, traffic systems, energy systems, healthcare systems, typologies, etc.) of interest from large masses of urban data, with each entity described by a large number of attributes. Which of these attributes gives us information on these entities' likelihood of contributing to environmental, economic, and social goals of sustainable development in the context of smart sustainable cities? How much information and how unexpected and unknown can it be? An urban analyst (or researcher) may be able to hypothesize some and investigate them further, and there are various tools available to facilitate this experimentation in the context thereof. This experimentation can alternatively be carried out in an automated and large-scale fashion by means of advanced ICT to automatically discover informative descriptive attributes of any entity of interest. This concept can be applied recursively to build models across various urban domains and sub-domains to predict events or situations based on multiple attributes, as well as prevent them from happening if they involve negative implications for one of the dimensions of sustainability.
- Formulating data mining solutions to urban sustainability problems across diverse urban domains and subdomains and evaluating the results entails thinking carefully about the physical, spatial, topographic, and temporal contexts in which such solutions will be implemented. This implies formulating the kind of solutions that can actually contribute beneficially to the goals of sustainable development when extracting potentially useful knowledge. This depends critically on the application domain of urban sustainability in terms of how exactly we plan to use the patterns extracted from urban data, whether in relation to operations, functions, designs, services, practices, or policies. The underlying assumption is to ensure that the extracted patterns lead eventually to enhanced decision-making and insights compared to other available reasonable alternatives in urban thinking about analytics problems pertaining to environmental, economic, and social sustainability.

- Overfitting a dataset describing some urban sustainability indicators related to, for example, mobility, traffic, utility, spatial behavior, and travel behavior is about attempting to find something in this dataset as a result of looking hard at it, an outcome that might not generalize beyond the data an urban analyst is looking at in a particular context. Overfitting occurs when random error and noise are created by too much flexibility that exists within the data, or simply when models are forced to fit the training data, as they are excessively complex, i.e., have too many parameters pertaining to the observations in the training set. This affects negatively the quality of models as to their ability to deliver generalization of data. Indeed, models should meet general populations and not have too many parameters focused only on the training data. In this case, a hyperplane (see Fig. 4.1), a data mining tool, separates a decision surface/boundary and hence classifies items according to one class or another, and can result in different outcomes. Thus, it is important to manage it to avoid any risk of misclassification. Indeed, choosing a hyperplane with small margins increases the risk of overfitting, and a model that has been overfit has poor predictive performance, as it overreacts to minor fluctuations in the training data. In short, with a hyperplane having a small margin, there is high chance of misclassification of new instances. Therefore, a large margin is preferred to maximize the minimum distance from the hyperplane to the nearest or closest training data point, as the fattest hyperplane separating the data tolerates most measurement error. The need to detect and avoid overfitting is one of the most important aspects to consider and grasp when applying data mining to real urban problems. The concept of overfitting and its avoidance is at the core of data science evaluation methods as well as algorithms and processes concerning a variety of big data analytics techniques.

Figure 4.1 shows two forms of hyperplane for classification. In the right-hand part of Fig. 4.1, there is one hyperplane with maximum margin separating small circles and squares as two different classes, and the linear classifier this hyperplane

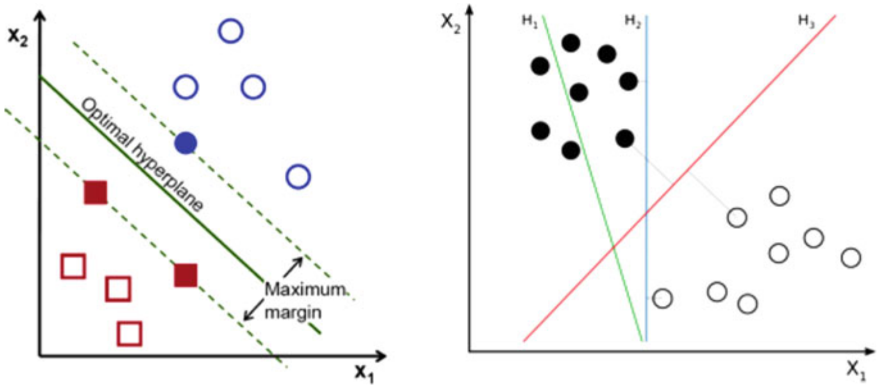


Fig. 4.1 Hyperplanes for classification

defines is known as the perceptron of optimal stability. In the left-hand part of Fig. 4.1, there are three hyperplanes: H_1 does not separate the two classes (black dots and white circles) while H_2 does separate them, but only with a small margin, and H_3 separates them with the maximum margin. In data mining, support vector machines (SVMs) as supervised data mining models involve algorithms that analyze data used for classification. Based on a set of training examples, each instance or example as described by a set of attributes (fields, variables, or features) is marked as belonging to one or the other of two classes. An SVM training algorithm builds a model that assigns new instances or examples to one class or the other through a clear gap, making it a non-probabilistic binary linear classifier. As points in space, new instances are then mapped into this space, thereby being predicted to belong to a class based on which side of the gap they fall under. When the aim is to decide which class a new instance will be based on some given examples each belonging to one of two classes, we speak of a linear classifier.

There are dozen other fundamental concepts of data science that can be considered in the domain of urban sustainability. The interested reader might want to read Provost and Fawcett (2013) for further details. The authors illustrate how such concepts aid in structuring data-analytic thinking and understanding data mining techniques quite generally, yet in relation to business intelligence applications and not urban sustainability applications.

4.2.2 Supervised Versus Unsupervised Learning Methods: Predictive and Descriptive Data Mining

The concepts of supervised and unsupervised learning were inherited from the area of machine learning, a subfield of artificial intelligence that deals with artificial systems that are able to improve their performance over time in response to their experience in the world. Supervised and unsupervised methods are applied to different types of data mining tasks (classification, regression, clustering, profiling, causal modeling, etc.), and hence underlie data mining techniques. They are also associated with other big data analytics techniques. Moreover, machine learning is, like data mining, closely related to and often overlaps with applied statistics, in terms of prediction-making through the use of computer systems.

The field of data mining is seen as an offshoot of the field of machine learning, and both fields remain closely linked, as they are associated with the analysis of data to discover informative patterns. In view of that, existing techniques and algorithms for knowledge discovery are used in both fields. Indeed, researchers from data mining and machine learning communities transitioned between them seamlessly. Research focused on urban sustainability applications and urban issues of data analysis tend to gravitate toward the data mining/knowledge discovery community rather than to machine learning.

In terms of the process of data mining (addressed below in more detail), a vital part in its early stages is to determine whether the line of attack will involve supervised or unsupervised methods prior to identifying which data mining techniques and algorithms are to be adopted. In supervised learning (predictive data mining), experience means that objects have been assigned class labels, and performance typically concerns the ability to classify new (previously unseen) objects. Accordingly, in the model generated by supervised learning, a relationship between a set of selected variables and a predefined target variable is described based on particular data. The model predicts the value of the target variable for unseen instances as a probabilistic function of other descriptive attributes. Examples of supervised learning in the urban domain include, but are not limited to, the following:

- Citizen travel behavior classification;
- Mobility and accessibility classification in high-density areas;
- Household energy consumption classification;
- Prediction of which typology (T1, T2, T3, or a combination of two or more of these) will a citizen likely prefer to be associated with his/her living or working environment in if given a kind of social or environmental incentive;
- Prediction of how GHG emissions will go in the next month (increase or decrease);
- Prediction of how energy consumption will go in the next month (increase or decrease);
- Prediction of areas of dense traffic in the near future;
- Prediction of travel behavior in connection with a set of combined typologies at a particular spatial level (neighborhood, district, city, etc.); and
- Spatiotemporal prediction of the development and propagation of congestion with small errors.

In unsupervised learning (descriptive data mining), experience entails objects for which no class labels have been given, and performance typically concerns the ability to output useful characterizations (or groupings) of objects. Examples of unsupervised learning in the urban domain include, but are not limited to, the following:

- Find useful travel behavior categories,
- Find interesting collective or individual mobility patterns,
- Find characteristic information about traffic jams and road congestion,
- Describe normal accessibility to facilities in urban areas characterized by mixed land use,
- Find groups of typologies that share similar features of environmental performance,
- Find groups of citizens that share similar travel behavior patterns within a given spatial scope,
- Find association rules between mobility or commuting behavior and environmental performance, and
- Discover the subgroups of travel characterized by common behavior, time length, and purpose.

While descriptive data mining focuses on finding patterns for human interpretation by producing nontrivial characteristic information on the basis of the available data set, predictive data mining use some variables in the dataset to predict future or unknown values of variables of interest (target) on the basis of models generated by training sets and described by particular data (attributes or features). Concerning descriptive data mining, there is no specific purpose specified for the grouping, i.e., there is no guarantee that the similarities generated from the grouping are useful for any particular reason, and hence the data mining problem is referred to as unsupervised. For example, consider a question we might ask about a mobility mode of citizens: Do citizens naturally fall into different categories?

Concerning predictive data mining, there is a specific target defined, and thus the data mining problem is referred to as supervised. Now we contrast our example with a slightly different question: Can we find groups of citizens who have particularly high likelihoods of walking and cycling when dwelling in an urban area characterized by mixed land use or diversity? In this case, segmentation can be done for a specific reason: to take action (promote and adopt mixed land use as a typology for sustainable mobility in newly developed urban environments) based on the likelihood of walking and cycling. In all, a supervised learning task is when the learner is provided with specific target information along with a set of examples (training data where the value for the target attribute is known), and an unsupervised learning task is when the learner might be provided with the same set of examples but without the target information, i.e., the learner would be left to draw its own conclusions (of descriptive nature) about what the provided set of examples has in common, as it would be given no information about the purpose of learning.

As we will exemplify next, supervised and supervised tasks entail different techniques, and the outcomes often are much more useful in relation to urban sustainability problems. Supervised methods are generally associated with classification, regression, and causal modeling, and unsupervised methods concern clustering, co-occurrence grouping, and profiling. As to link prediction, similarity matching, and data reduction, they could be solved either with unsupervised or supervised methods. In particular, the methods for extracting predictive models from data using supervised methods have been investigated and developed in several scientific fields contemporaneously, most notably applied statistics, machine learning, and pattern recognition. These fields have, therefore, become so closely tied that the separation between them has blurred.

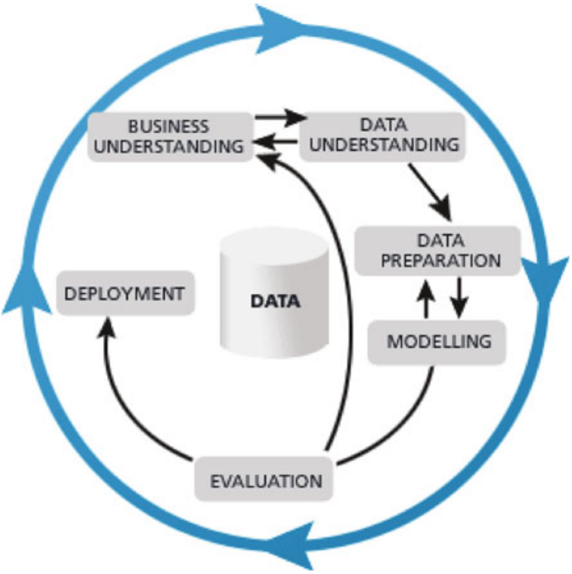
4.3 Related Work

4.3.1 Big Data Analytics and Data Mining

Research on big data analytics (and data mining) has been active since the mid-1990s (e.g., Fayyad et al. 1996; Laney 2001; Kurgan and Musilek 2006; Shearer 2000; Ponce and Karahoca 2009; Shearer 2000), and many books (e.g., Ponce and Karahoca 2009; Provost and Fawcett 2013) have been written on the topic from a business intelligence perspective. Furthermore, many reviews or surveys have been conducted in recent years on big data analytics. While they offer different perspectives on, and highlight various dimensions of, the topic, they overlap in many computational, analytical, and technological aspects (Bibri and Krogstie 2017c). Also, they are more often than not oriented toward business intelligence (see, e.g., Chen et al. 2012; Provost and Fawcett 2013). And they tend to put emphasis on different components of big data analytics, such as techniques, algorithms, software tools, platforms, and applications. Chen et al. (2015) provide a systematic review of data mining in technique view, knowledge view, and application view, supported with the latest application cases related mostly to business intelligence. Singh and Singla (2015) provide an overview of the leading tools and technologies for big data storage and processing, throw some light on other big data emerging technologies, as well as cover the business areas from which big data can be generated. In their review, Tsai et al. (2015) discuss big data analytics and related open issues, focusing on how to develop a high-performance data processing platform to efficiently analyze big data and to design an appropriate mining algorithm to extract useful knowledge from big data, in addition to presenting some research directions. One of the aspects emphasized in their work is the steps (selection, preprocessing, transformation, mining, and interpretation/evaluation) of the whole process of knowledge discovery in databases (KDD), as summarized by Fayyad et al. (1996). Most of research articles focus typically more on data mining than other steps of KDD process. Tsai et al. (2015) simplify the whole process into three parts (input, data analytics, and output) and seven steps (collection, selection, preprocessing, transformation, mining, evaluation, and interpretation). Katal et al. (2013) provide a varied discussion covering several big data issues, challenges, tools, characteristics, sources, and best practices in relation to such applications as social media, sensor data, log storage, and risk analysis. Chen et al. (2014) review the big data background and the associated technologies, including applications and challenges (in relation to data generation, acquisition, storage, and analysis). Given the paucity of survey work on the core enabling technologies of big data analytics in the context of smart sustainable cities, Bibri and Krogstie (2017c) have recently conducted a review of the technical literature with the objective of identifying and synthesizing such technologies and illustrating the key computational and analytical techniques and processes associated with the functioning of big data ecosystem, including the process of data mining.

There is a large body of work that addresses CRISP-DM (see Fig. 4.2) (e.g., Kurgan and Musilek 2006; Marbán et al. 2009; Ponce and Karahoca 2009; Chapman et al. 2000; Shearer 2000). This process emphasizes the idea of iteration. This implies that solving a particular problem may require going through the process more than once. The entire process is an exploration of the data and how it can be integrated. The rationale for the iteration is for the group of data scientists to increase their understanding and hence gain more knowledge as they explore the problem and devise the right solution to it. Also, the lessons learned during the process can trigger new, often more focused sustainability questions, and

Fig. 4.2 Data mining process



subsequent data mining processes will benefit from the experiences of previous ones. In addition, the sequence of the components is not strict and moving back and forth between different components is always required. The arrows indicate the most important and frequent dependencies between the components. The outer circle symbolizes the cyclic nature of data mining itself. A data mining process continues after a solution has been deployed.

The CRISP-DM defines six phases:

1 Business understanding
2 Data understanding
3 Data preparation
4 Modeling
5 Evaluation
6 Deployment

However, the data mining process model exists in many variations, e.g., a simplified process like (1) Preprocessing, (2) Data Mining, and (3) Results Validation. The literature shows that the CRISP-DM methodology is the leading methodology used by data miners. Several teams of researchers have published reviews of data mining process models (e.g., Kurgan and Musilek 2006; Marbán et al. 2009).

As one of the prerequisite technologies for realizing the prevalent ICT visions of pervasive computing (e.g., the IoT and UbiComp), big data analytics entails extracting useful knowledge from large masses of data for enhanced decision-making and insights pertaining to a large number and variety of urban domains in the context of sustainability (Bibri and Krogstie 2016). However, research on big data analytics has been active in the realm of smart cities, dealing largely with economic growth. For example, Hashem et al. (2016) discuss the visions of big data analytics to support smart cities by focusing on how big data can fundamentally change urban populations at different levels. They also propose future business model of big data for smart cities and identify the business and technological research challenges. But the role of big data analytics in advancing and transforming the knowledge of sustainability in the context of smart sustainable cities as a holistic urban development approach is barely explored to date (Bibri 2018c). In other words, despite the proliferation of the literature and thus the increase of the research on big data analytics, the bulk of work tends to deal largely with smart cities in terms of business intelligence applications and citizen services (e.g., Batty 2013; DeRen et al. 2015; Khan et al. 2015; Kitchin 2014; Ji et al. 2012; Kumar and Prakash 2014; Townsend 2013; Wan et al. 2016), thereby hardly exploring the role of big data analytics in improving the contribution of smart sustainable cities to the goal of sustainable development as a result of advanced analytics. The way forward for future cities to advance sustainability is through advanced ICT that ensures the utilization of big data analytics (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri and Krogstie 2017b). In the near future, the core enabling technologies of big data analytics, namely digital sensing technologies, data processing platforms, cloud and fog computing models, and wireless communication networks, will be the dominant mode of monitoring, understanding, and analyzing smart sustainable cities as to their operational functioning, planning, and governance to improve their contribution to the goal of sustainable development (Bibri and Krogstie 2016).

4.3.2 Data Processing Platforms

There are different data processing platforms being used in various sectors for handling the storage, analysis, and management of large datasets, depending on a variety of technical requirements and objectives. Irrespective of the application area to which big data are applied, big data analytics is associated with some kind of data processing platforms for handling the analysis and management of large datasets. Data processing platforms are a key component of the ICT infrastructure of smart sustainable cities with respect to big data applications. Among the leading platforms for big data storage, processing, and management include Hadoop MapReduce, IBM Infosphere Streams, Stratosphere, Spark, and NoSQL-database system management (e.g., Al Nuaimi et al. 2015; Fan and Bifet 2013; Khan et al. 2015; Singh and Singla 2015). As ecosystems, they perform big data analytics related to a wide variety of large-scale applications intended for different uses associated with the process of sustainable urban development, such as management, control, optimization, assessment, and improvement, thereby spanning a variety of urban domains and sub-domains. Moreover, they are used for such tasks as implementing data mining techniques or data processing in support of the data mining techniques of data science activities, including scientific and academic research. For a detailed account and discussion of Hadoop MapReduce in relation to big data applications for better understanding of the characteristics, components, and functionalities of data processing platforms in the context of smart sustainable cities, the interested reader can be directed to Bibri (2018a, b). Hadoop MapReduce has become the primary big data processing system given its simplicity, scalability, and fine grain fault tolerance (Zhang et al. 2016). As stated by Singh and Singla (2015), Hadoop allows to distribute the processing load among the cluster nodes, which enhances the processing power; to add or remove nodes in the cluster according to the requirements; and to make the homogenous cluster with various group of machines instead of the costly option of using one supercomputer, and to handle unstructured data. Another benefit of Hadoop is that it is free of charge for different commercial uses because it is an open source architecture. There are different extensions of Hadoop, which are usually considered for comparison, including HadoopDB, Co-Hadoop, Hadoop++, and Dare (Singh and Singla 2015). Hadoop is a framework for data management on which MapReduce works as a programming model, and its functionality is based on batch processing: dividing the big task into small subtasks and then executing them in parallel. Numerous technologies (e.g., Apache PIG, Apache HBase, Apache Hive, Apache Scoop, Apache Flume, Apache Cassandra, Scribe, Apache Zookeeper, and many more) can be built on the top of the Hadoop system to form a Hadoop ecosystem along with HDFS to enhance the efficiency and functionality of Hadoop (Singh and Singla 2015). Karun and Chitharanjan (2013) provide a whole review on Hadoop in terms of HDFS infrastructure extensions, making a comparison of Hadoop Infrastructure Extensions (HadoopDB, Hadoop++, Co-Hadoop, Hail, Dare, Cheetah, etc.) on the basis of scalability, fault tolerance, load time, data locality, and data compression. While Hadoop is originally developed for use in the domain of business intelligence (e.g., customer buying behavior, advertisement targeting, user recommendation, retail, and search quality), its uses are increasingly being extended to include several urban domains in the context of smart cities and smart sustainable cities in connection with big data applications. For instance, Khan et al. (2015) develop a prototype to demonstrate the effectiveness of big data analytics, and implement it using Hadoop and Spark for the purpose of comparing the results in terms of the suitability of these two data processing platforms. To note, Spark is more efficient in terms of real-time data processing, which is of relevance to the IoT applications. Further, the authors present a theoretical and experimental perspective on the use of big data analytics in smart cities. Their prototype analyzes an open dataset to identify statistical correlations between a set of selected urban environment indicators of the quality of life, such as health, well-being, employment, air quality, housing, income, and crime. Another project that uses Hadoop for big data analytics in the context of smart city is government city administration, where Hadoop architecture is used to, quoting Neirotti et al. (2014), "manage real–time analysis of high volume data, develop a massively scalable, clustered infrastructure…for discovery and visualization of information from thousands of real–time sources, encompassing application development and systems management built on Hadoop, stream computing, and data warehousing" (Al Nuaimi et al. 2015, p. 7). Another software system is

Apache S4: a platform designed specifically for managing and processing continuous data streams in real time (Neumeyer et al. 2010). When dealing with IoT, real–time data processing approaches, like Apache Storm, should also be considered. In their survey, Zhang et al. (2016) explore new research opportunities and provide insights into selecting suitable processing systems for specific applications, providing a high-level overview of the existing parallel data processing systems categorized by the data input as stream processing, machine learning processing, graph processing, and batch processing.

4.3.3 Big Data for Urban Analytics

In recent years, the concept and application of big data analytics has been expanded beyond the ambit of business intelligence to include the area of urban development as to such domains as energy, transport, mobility, traffic, power grid, building, environmental monitoring, planning, design, policy, governance, healthcare, education, and other social and public services in the context of sustainability (e.g., Al Nuaimi et al. 2015; Angelidou et al. 2017; Batty et al. 2012; Bettencourt 2014; Bibri 2018a; Bibri and Krogstie 2017b; Khan et al. 2015; Kumar and Prakash 2014). However, the literature on the uses of big data analytics in relation to sustainability problems, i.e., “big data” studies, in the context of smart sustainable cities remains scant, whether be it on descriptive and predictive data mining or on other big data analytics techniques. This is probably because the concept of smart sustainable cities did not became widespread until the mid-2010s, and hence research is still in its early stages (e.g., Bibri and Krogstie 2017a), including what forms of analytics should be used in this research for advancing the knowledge of such cities.

Nagarkar (2017) provides a short review on data mining techniques and applications to support the smart city endeavor. The author state that most of the scientific organizations generate large amount of data, and effective analysis and utilization of these gigantic data is a key factor for success in many fields, which includes the smart sustainable city domain. Bibri and Krogstie (2017c) briefly describe and illustrate the process of data mining as applied to urban sustainability problems. It consists of these stages: urban sustainability problem understanding, data understanding, data preparation, model building, results evaluation, and results deployments. The authors state that one of the fundamental concepts of data science is the automated extraction of useful knowledge from large masses of urban data to solve urban sustainability problems (physical, environmental, social, and economic) related to diverse urban domains (energy, transport, mobility, traffic, environment, land use, health care, education, etc.). This can be treated systematically by following a set of reasonably well-defined stages, a process that provides a framework to structure urban thinking about data analytics problems related to different dimensions of sustainability. In the context of smart sustainable urban planning and development as a set of enhanced practices, it is important to devise analytical solutions based on careful analysis and evaluation of the relevant problems using high-powered analytical and evaluative tools, as well as creativity, common sense, and specialized knowledge (Bibri and Krogstie 2017c). However, the authors provide neither the detailed description of the stages of the process of data mining nor the explanation of how this can be done in relation to urban sustainability. In relation to this, Bibri (2018a) provide a detailed account of the different data mining techniques, algorithms, and tasks based on supervised and unsupervised methods, supported with illustrative examples related to smart sustainable cities. According to the author, most urban sustainability problems can be transformed to one or several data mining tasks, including classification, clustering, regression, co-occurrence grouping, similarity matching, profiling, and causal modeling. Also, Chen et al. (2015) deliver a systematic review of data mining in technique view, knowledge view, and application view, supported with application cases related mostly to business intelligence though. However, a well-understood process of urban analytics places a structure on the problems pertaining to urban sustainability, allowing reasonable consistency, repeatability, and objectiveness. The objective of the process of data mining is to discover new knowledge in large masses of urban data pertaining to different sustainability dimensions to improve the environmental and socioeconomic performances of smart sustainable cities. Accordingly, such process is concerned with solving problems related to the spatial, physical, infrastructural, operational, and functional forms of such cities in the context of sustainability. For an optimal outcome in the case of spatial data mining, for example, it is invaluable to integrate different methods (spatial analysis, spatial statistics, fuzzy logic, probability theory, cluster analysis, etc.), especially these methods are not mutually exclusive (DeRen et al. 2015). As to the spatial data, they include such features as spatial, massive temporal, massive multidimensional, and complex (Li et al. 2006). In this regard, DeRen et al. (2015) propose a strategy to handle big data that focuses on data mining. They provide a detailed analysis of the big data mining process related to integrated space and attributes. The process includes the processing and analysis of mass and multisource data, automatically discovering and extracting implicit patterns and knowledge, and visualizing and integrating them into a presentation that is understandable by humans. The specific procedure consists of data retrieval and storage, data processing and analysis, data mining (clustering or classification), data visualization, data fusion and information extraction are relatively more difficult to conduct. However, like many data mining processes available in the literature, this process is oriented toward carrying out automatic tasks associated with operations and functions across smart cities. It is not suitable for investigating and analyzing specific urban sustainability problems (energy, traffic, mobility, healthcare, planning, design, etc.) of concern to researchers, scholars, planners, and city analysts in collaboration with data scientists that could improve the contribution of smart sustainable cities to the goals of sustainable development.

In addition, Pappalardo and Simini (2016) focus on the generation of realistic spatiotemporal trajectories of human mobility in relation to a wide range of applications, such as what-if analysis in urban ecosystems. They specifically present a diary-based trajectory simulator, a framework to simulate the spatiotemporal patterns of human mobility and functions based on the generation of a mobility diary and the translation of the mobility diary into a mobility trajectory. The authors demonstrate that the proposed algorithm reproduces the statistical properties of real trajectories in an accurate way, making a step forward the understanding of the origin of the spatiotemporal patterns of human mobility. Their work does not specify any use of the system in relation to urban operational functioning and planning processes associated with the contribution of cities to the goals of sustainable development. In Towards a Better Understanding of Cities Using Mobility Data, Lenormand and Ramasco (2016) present an overview of recent findings in empirical applications of big data on mobility to the systematic study of cities and their problems of movement. This is of relevance to the topic of this paper: city-related scientific and academic research. The authors discuss the potential of this new source of data and how the coupling of big data analysis and computational modeling and simulation can open new horizons for the analysis of urban systems. However, no systemic framework (e.g., data mining or knowledge discovery process) was provided for how to analyze activity and mobility patterns in urban environment in the event of the increasing availability of geolocated data generated by the use of ICT. But they do highlight the potential of ICT to provide a solution for handling more efficiently new and extensive sources of data, to gain a better understanding of urban dynamics and human mobility, and to search for more sustainable living conditions.

4.3.4 ‘Big Data’ Studies: Academic and Scientific Research

Big data are referred to with respect to their humongous size and wide variety, with particular attention on the urban data (i.e., datasets collected and coalesced through data warehousing for wide-city uses) that are directed toward advancing smart sustainable cities in terms of sustainability and the integration of its dimensions. This epitomizes a sea change in the kind of data that we generate about urban systems and domains as to what happens and where, when, why, and how in the context of smart sustainable cities. Bibri (2018a) argues that data mining and knowledge discovery have innovative potential to advance urban analytics in the form of “big data” studies by providing a novel way of thinking data-analytically about urban sustainability problems. And by enabling well-informed or knowledge-driven decision-making and enhanced insights in relation to diverse urban domains with regard to operations, functions, strategies, designs, practices, and policies for increasing the contribution of smart sustainable cities to the goals of sustainable development. Especially, “small data” studies—questionnaire surveys, focus groups, case studies, participatory observations, audits, interviews, content analyses, and ethnographies—“capture a relatively limited sample of data that are tightly focused, time and space specific, restricted in scope and scale, and relatively expensive to generate and analyze, to provide additional depth and insight with respect to specific phenomena.” Kitchin (2014, p. 3). For example, as mentioned by Batty et al. (2012), the mainstream analytical tools of transportation engineering, such as origin/destination matrices, are based on semantically rich data collected by means of field surveys and interviews. In a nutshell, much of what we know about cities to date has been gleaned from studies that are characterized by data scarcity (Miller 2010). The prevailing form of academic and scientific research has, over the past 25 years, had implications for the way urban sustainability as a set of practices underpinned by theoretical perspectives has been adopted in city planning and development.

The potential and hope of big data lies in transforming the knowledge and governance of cities through the creation of a data deluge that seeks to provide much more sophisticated, wider scale, finer grained, real-time understanding, and control of various aspects of urbanity (Kitchin 2014), including sustainability. Big data can be used to overcome the constraints and limits of traditional data collection and analysis methods, namely their high cost, infrequent periodicity, quick obsolescence, incompleteness, reflexivity, and inaccuracy in the domain of urban planning and development (Batty et al. 2012; Bettencourt 2014; Bibri 2018b; Bibri 2018a, b; Kitchin 2014). These issues have indeed long affected the robustness and reliability of research results (theories, generalizations, etc.) within the field of urban sustainability. This has, in turn, impacted on urban practices in terms of the application of the principles and methods of sustainability in urban planning and development, to reiterate. Many studies investigating, or referring to other research work carried out on, the correlation between travel behavior (walking, cycling, car driving, etc.) and other indicators of environmental performance, on the one hand, and density, compactness, diversity, mixed” land use, and other typologies through which sustainable urban forms can be achieved, on the other hand, point implicitly or explicitly to the disadvantages of the traditional data collection and analysis methods and how they compromise the value of the obtained research results (Bibri and Krogstie 2017b; Jabareen 2006; Neuman 2005). These studies usually generate non-conclusive, weak, limited, unreliable, conflicting, or uncertain results. The interested reader might want to read a recent article by Bibri and Krogstie (2017b), where a detailed discussion is provided on several topics related to sustainable urban forms, including, in addition to big data analytics as an alternative to traditional data collection and analysis methods for investigating sustainable urban forms, the role of big mobility data in evaluating the environmental performance of sustainable urban forms, urban simulation models as an approach into strategically assessing and optimizing the contribution of sustainable urban forms to sustainability, and big data as the basic ingredient for the next wave of sustainable urban form analytics.

4.4 From Urban Sustainability Problems to Data Mining Tasks

Each data-driven decision-making problem as part of urban analytics is unique, consisting of its own combination of objectives, requirements, and constraints. However, there are sets of common data mining tasks that underlie the urban sustainability problems pertaining to various urban domains. In collaboration with urban stakeholders (authorities, departments, administrators, institutions, enterprises, etc.), city analysts, researchers, scholars, and planners, data scientists decompose an urban sustainability problem into subtasks, and the solution can subsequently be composed to solve such problem. This may relate to energy, transport, traffic, built environment, health care, education, safety, or other urban (application) domains. The know-how of data scientists resides in their ability to decompose a data analytics problem of a particular aspect of urban sustainability into subtasks for which tools and techniques are available and can be used separately or combined. Obviously, some of these subtasks remain common data mining tasks, and others are unique to the particular urban sustainability problem. For instance, a mobility problem can be unique or specific to a given district, city, or region as spatial scales, and would depends on how sustainable or smart these spatial scales are, adding to the other factors associated with urbanization: there are specifics of the problem that are different from mobility problems of any other district or city. Nonetheless, a subtask that will likely be part of the solution to any mobility problem is to estimate from historically stored urban data on mobility the probability of a citizen living in a particular district choosing a particular transport mode or travel behavior. So, this probability estimation fits the mold of one of the common data mining tasks on the basis of how mobility data are assembled into a particular format in relation to a given district, city, or region.

In recent years, there has been a major shift in scientific and practical knowledge used to solve the common data mining tasks. Overall, what matters in data analytics problems in the context of urban sustainability is to possess the ability of recognizing urgent and common problems and their solutions, and doing this in ways that avoid wasting resources and time by reinventing the wheel when considering new urban projects associated with data analytics for advancing urban sustainability with regard to various urban domains. This implies that the data mining process in this context is not only about the automated extraction of useful knowledge from data for enhanced decision-making and insights, but also about creativity, common sense, and acumen, and so on.

Data mining focuses on the automated search for useful knowledge through finding patterns, regularities, and correlations in data. And it is important for the urban analysts (affiliated with, for example, city authorities, urban departments, enterprises, and institutions) to be able to recognize what sort of the analytic techniques among the available ones (data mining, machine learning, statistical analysis, regression analysis, database querying, data warehousing, etc.) is appropriate for addressing a particular urban sustainability problem within a given urban domain. The fundamental principles of data mining underlie a number of types of techniques, including classification, regression, causal modeling, similarity matching, link prediction, data reduction, clustering, and co-occurrence grouping. For example, distinguished by the kind of target, classification and regression are two common subclasses of supervised data mining, and clustering and co-occurrence are two common subclasses of unsupervised data mining, to reiterate. For a detailed illustration of the fundamental principles of data science that underlie the different tasks of these techniques, the interested reader might start by reading the relevant chapters from Provost and Fawcett (2013). However, the use and combination of these techniques often depends on the nature of the urban sustainability problem to solve or tackle, as we will exemplify below. Although there are a large number and variety of specific data mining algorithms developed hitherto (from such fields as machine learning, statistics, artificial intelligence, database systems, and pattern recognition) to perform different data analysis tasks, there are only a small amount of fundamentally different kinds of tasks these algorithms perform. The tasks apply to, in the context of smart sustainable cities, different kinds of human or inanimate entities (e.g., citizen, mobility system, utility system, traffic system, transport system, energy system, travel behavior, typology, etc.) about which we have data. In many urban sustainability analytics projects, the desire is to find correlations between a particular variable describing an entity and other variables. For example, in urban data, whether of a historical or real-time character, we may know which typologies (density, diversity, mixed land use, etc.) are environmentally sound across a particular spatial scale, which citizens are environmentally sustainable in terms of travel behavior, or which traffic conditions cause endemic congestions. We may want to find out which other variables correlate with a typology being environmental sound across a particular spatial scale, and similarly, which other variables correlate with a citizen being environmentally sustainable in terms of travel behavior and with traffic conditions causing endemic congestions. Finding such correlations illustrates the most basic examples of classification tasks. The data mining tasks considered of relevance to the domain of urban sustainability are described and exemplified next.

4.4.1 Classification

As a common predictive task in data mining, classification and class probability estimation attempt to predict, for each entity (or sub-entity), which of a small set of (often mutually exclusive) classes this entity belongs to. It is about discovering a predictive learning function that classifies a new example or instance into one of several predefined classes. Classification is the most commonly applied data mining technique in many urban domains. An example classification question related to the built environment would be: Of the existing typologies or design concepts of sustainable urban forms, which are likely to optimize energy efficiency, minimize automobile travel needs, reduce the need for mobility, enhance accessibly to facilities and services, encourage cycling and walking, reduce air pollution and traffic congestion, and/or enhance the quality of life in terms of social interaction? In this example, the two classes could be called one of the respective attribute value and its negation. See the other examples given in the previous section. For a detailed overview of the typologies of sustainable urban forms and their descriptive features, the interested reader can be directed to Bibri and Krogstie (2017b). For a classification task in this context, a data mining procedure generates a model that, given a new entity focused on a particular dimension of sustainability or integrating different dimensions of it, determines which class that entity belongs to in relation to environmental, social, and/or economic sustainability based on the multi-value of the target variable.

A task closely related to class prediction is class probability estimation, a scoring model applied to an entity that generates a score representing some quantification of the likelihood (e.g., probability) that that entity belongs to each class label (e.g., the probability of a given typology to reduce air pollution and traffic congestion at a particular spatial scale). In this context, a scoring model would be able to evaluate each typology and generate a score of how likely each is to contribute to which dimension of sustainability in the context of sustainable urban forms. Generally, a model can be adjusted to do both classification as well as scoring. These are indeed very closely related. Classification algorithms (classifiers) include decision tree induction, Bayesian network, SVMs, K-nearest neighbor, case-based reasoning, back propagation, rough set approach, and fuzzy set approach. They entail two processes: data training (learning) and data testing (classification). In learning, the training data are analyzed to generate a model based on pre-classified examples to determine the set of parameters needed for fine-grained and proper discrimination, and in classification, the test data use this model to estimate the accuracy of the classification rules and then apply the model as a set of classification rules to new data tuples.

4.4.2 Regression

Regression is related to, yet different from, classification. Regression is about value estimation, as it involves a numeric target, in contrast to classification which involves a categorical target. It attempts to estimate the numerical value of some variable for each entity. As a data mining task, it can be used to model the relationship between one or more independent variables (attributes already known) and response variables (attributes to be predicted or estimated). An example regression question would be: How much will a given citizen benefit from a health care, utility, transport, or education service in a given district or city? The property (variable) to be estimated here is the quality of life in terms of the usage of these types of services. In this context, a model could be generated by looking at other citizens in the context of smart sustainable cities and their usage of services compared to, for example, sustainable cities or smart cities. A regression generates a model that estimates the value of the particular variable specific to a given citizen in this context. Consider similar questions that can be addressed with supervised data mining: Will or how easy will a given citizen benefit from a facility in the case of a particular typology (mixed land use, density, diversity, etc.)? Which kind of service will a citizen likely have access to easily if provided with smart technologies? These are classification problems because they have a categorical target (often binary). These problems can have a multivalued target. The target variable in the case of regression is the amount of actual or estimated usage of a given service per citizen in the context of smart sustainable cities. In all, while regression estimates how much something will happen, classification predicts whether something will happen. Regression algorithms include multivariate linear, nonlinear, and multivariate nonlinear methods. As with classification, a model can be adjusted to do regression and classification. For example, neural networks and decision trees algorithms can be used to produce both regression trees (to estimate continuous target variables) as well as classification trees (to classify categorical target variables).

4.4.3 Clustering

As a common descriptive task, clustering attempts to group entities (e.g., citizens' profiles or individual mobility patterns in relation to density, diversity, mixed land use, sustainable transport, etc.) together by their similarity by identifying clusters (based on similar classes of objects) to describe the data. This is, however, not driven by any specific purpose, to reiterate. Clustering, as a by-product of its normal function, allows for identifying dense and sparse regions in object space as well as for discovering distribution patterns and correlations among data attributes. An example clustering question in the context of smart sustainable cities would be: Which class of citizens mostly uses sustainable transport or cycle? Do citizens form natural segments in connection with density or mixed land use? Do mobility patterns vary depending on existing typologies across spatial scales? Clustering can be very useful in preliminary exploration pertaining to various urban domains to see which kind of grouping exists, as this grouping, in turn, may suggest other data mining approaches whose analytical outcomes may contribute to improving, integrating, or rethinking certain typologies as spatial organizations through enhanced insights which can be deployed as part of new urban strategies and practices. Indeed, clustering can also be used as input to decision-making processes focusing on questions such as: What kind of spatial organizations should we promote or mainstream to improve environmental sustainability performance? What sort of urban energy source or grid system should we use in the case of a particular set of organized and coordinated typologies (physical arrangement) across diverse spatial scales? How smart technologies could be amalgamated with urban structures to shape mobility patterns in ways that reduce traffic congestion and air pollution? How should physical arrangements be better structured and effectively integrated with smart technologies? Clustering algorithms encompass methods and their techniques, including hierarchical (divisive and agglomerative), partitioning (relocation, probabilistic, K-medoids, K-means, density-based (connectivity and function), grid-based (co-occurrence of categorical data, constraint-based, gradient descent, artificial neural networks, and evolutionary), and model-based (high dimensional data, subspace, projection, and co-clustering).

4.4.4 Similarity Matching

Similarity matching is another task of data mining procedure, which attempts to identify or find similar entities of a certain type based on data known about these entities. For example, an urban analyst may be interested in finding similar citizens in terms of travel behavior, mobility form, or energy consumption level, and then looks for whether these are being shaped by certain urban strategies (e.g., typologies or other planning principles) or only by socioeconomic or behavioral factors. This may suggest other data mining approaches. Similarly matching can also be used as input to decision-making processes focusing on questions pertaining to transport engineering, sustainable mobility systems (e.g., car sharing and bicycle sharing), economic forecasting, and so on across different spatial scales. Indeed, similarity measures underlie certain solutions to such tasks as classification, regression, and clustering.

4.4.5 Co-occurrence

Co-occurrence grouping is also a common data mining task, which attempts to find associations between entities based on observational, statistical, or transactional datasets involving them. It is also referred to as frequent itemset mining and association rule mining. This relates to association analysis, which entails discovering association rules showing attribute-value conditions that occur frequently together in a given dataset. One of the algorithms used for finding frequent itemsets is Apriori algorithm which aims at finding frequent itemsets on the basis of monotonicity, i.e., an item set cannot be frequent unless all of its subsets are so. Other algorithms include multilevel, multidimensional, and quantitative association rules. They need to be able to produce rules with confidence values less than one. An example co-occurrence question would be: What indicators of the quality of life pertain to or are common to citizens in a particular district or city? In this example, while clustering looks at the similarity between citizens based on their attributes, co-occurrence grouping considers the similarity of citizens based on their attributes appearing together in a dataset. In their prototype implemented using the Hadoop architecture for big data analytics for smart cities on the basis of cloud computing infrastructure, Khan et al. (2014) apply a priori technique, a rule-based data mining algorithm, to learn rules from an open dataset. Their prototype analyzes an open dataset to identify statistical correlations between selected urban environment indicators of the quality of life, such as health, well-being, employment, air quality, housing, and crime. Discovering such correlations (frequency) is associated with decision-making purposes, which may involve some creativity in terms of suggesting initiatives for enhancing the socioeconomic performance of sustainability in the context of smart sustainable cities. The result of co-occurrence grouping is a characterization of items or attributes that occur together among instances of large datasets. These characteristics usually encompass statistics on the frequency of the co-occurrence based on the aim guiding the case of a decision-making problem, and usually an estimate of how unpredictable or unexpected the co-occurrence is.

4.4.6 Profiling

Applicable to a citizen, group, or population in a given city in this context, profiling is about behavior description. This typical characterization of behavior may be associated with mobility system, travel behavior, transport mode, utility service, healthcare service, household structure, and so on. An example profiling question would be: What is the typical transport/travel mode used by a group of dwellers of a particular district? Usually, behaviors may have simple or complex descriptions depending on the application domain; profiling a citizen, in this case, might require a description of day and weekend time travel, transport vehicle, travel frequency, travel distance, and so on. Behavior can be described generally over individual citizens, a small group of citizens, or even an entire population of a city. Profiling can be used in the context of smart sustainable cities to establish behavioral norms concerning aspects related to environmental, social, and economic sustainability applications. For example, if we know what kind of travel preferences a citizen typically makes in a particular district, we can determine how we can provide sustainable or efficient mobility systems (bicycle, car sharing, public transport, etc.) based on a certain profile of a group of citizens to promote environmental sustainability.

4.4.7 Link Prediction

Link prediction attempts to predict a connection between data items as well as estimates the strength of that connection. There are numerous examples of link prediction one can think of in the context of smart sustainable cities. One class of examples concerns the link between diverse typologies and design concepts of sustainable urban forms and the indicators of environmental and socioeconomic performances. Bibri and Krogstie (2017b) provide and explain important correlations in this regard, e.g., between mobility and spatial interaction, density and energy efficiency, mixed land use and cycling and walking, social interaction and spatial proximity, and so on. Beyond this class of examples, link predication as a data mining task often is more interesting when focusing on searching for links that do not exist between typologies and environmental indicators or citizens and indicators of the quality of life and well-being, but that we predict should exist and should be strong. Using graphs, these links form the basis for recommending some changes to urban practices or policies in ways that enhance the contribution of smart sustainable cities to the goals of sustainable development or integrate the dimensions of sustainability by, for example, promoting or combining certain typologies through zoning, or encouraging the use of smart technologies for enhancing sustainable urban living.

4.4.8 Data Reduction

Applied to colossal datasets, data reduction attempts to reduce the amount of the data intended for processing by taking a large dataset and replace it with a small one that contains the most relevant or much of the important information in the larger one. The main purpose of using small datasets instead of large is reducing the complexity associated with the computational and analytical techniques involved in solving a particular urban sustainability problem. In addition, the use of the small dataset may still achieve the intended goal as long as it better reveals the information needed for further processing. For example, a massive dataset on mobile movements of citizens may be reduced to a much smaller dataset revealing the activities that are associated with environmental indicators in terms of GHG emissions (for example, the use of an automobile to go to close shopping and leisure facilities). Another detailed example taken from Batty (2013, pp. 277–278) states: “We have 1 billion or so records of all those who have tapped ‘in’ and ‘out’ of the public transport systems deploying the smart ‘Oyster’ card for paying for travel.… The time period for the data is over 6 months… The data set is remarkable in that we know where people enter the system and leave it, apart from about 10% of users who do not tap out due to open barriers. The data set is thus further reduced in its comprehensiveness. Because tap-ins and tap-outs cannot be associated with origins and destinations of trips, we cannot easily use this data in our standard traffic models without some very clever detective work on associating this travel trip data to locations of home and work and other land-use activities. This is possible by good estimation but requires us to augment and synthesize the data with other independent data sets, and thus there is always error.” This is a good example of how data-driven urban analytics shapes urban planning in terms of using traffic models of effective patterns and correlations between travel behavior and locations of home and work and other land use activities. However, while data reduction involves loss of information under normal conditions, the trade-off for enhanced insights remains of importance.

4.4.9 Causal Modeling

Causal modeling is about providing insights into understanding what actions or events actually influence others. For example, in the case of using predictive modeling to target car or bicycle sharing promotion to a particular class of citizens, and we observe that indeed the targeted citizens adopt such a sustainable mobility system at a higher rate subsequent to having been targeted. Was this because the promotion influenced the citizens to adopt it? Or did the predictive model simply performs well as to identifying those citizens who would have adopted it anyway? Associated with what is viewed as "counterfactual" analysis, sophisticated methods for drawing causal conclusions from observational datasets as well as randomized controlled experiments as techniques for causal modeling generally attempt to understand what would be the distinction between the actions taken by a group of citizens in a particular situation—which cannot occur—where the treatment event (e.g., car or bicycle sharing promotion) were to occur, and were not to occur (see Provost and Fawcett 2013). Too often, data scientists involved in solving urban sustainability problems should always provide the exact assumptions underlying a causal conclusion in order for it to hold in a particular urban domain like energy, transport, and planning.

To sum up, a detailed discussion of the above tasks of data mining with illustrative examples covering various domains in relation to the different dimensions of sustainability in the context of smart sustainable cities would fill multiple books. The basic idea is that many of these types of tasks fit diverse sustainability problems in the context thereof, including classification, regression, clustering, causal modeling, link prediction, and data reduction. Further, to decide the best formulation for a given urban sustainability problem, it is important to highlight a key distinction pertaining to data mining, namely the process of mining the data to find patterns and correlations by building models and then using the results of this process. Urban analysts or administrators may confuse these two processes when discussing urban sustainability analytics. Following data science principles, although the two processes should be kept distinct, the data mining process is influenced and informed by the use of data mining results. As an example, consider the deployment scenario in which the results will be used in a predictive model, performing data mining on a historical urban dataset pertaining to individual mobility where training data have all values (the target class) specified produces a model that can be used to test a new data item (new, unseen instance) for which we do not know the class value to predict the value of the target class, as well as the probability that this class variable will take on that value.

The above data mining tasks relate to different analytics methods, including descriptive (what happened?), diagnostic (why did it happen?), predictive (what will happen?), and prescriptive (what should be done?) used to solve different decision-making problems related to urban sustainability in terms of urban operations, functions, services, designs, strategies, practices, and policies. The first three types of analytics are concerned with decision-making and its support, which entails human intervention, the level of which would vary depending on the nature of the application in connection with various urban domains and sub-domains. The last one is associated with decision automation and some kind of decision support. The targets of decision-making and action-taking are associated with the operating and organizing processes of urban life in line with the goals of sustainable development.

4.5 The Data Mining Process: Data-Analytic Solutions to Urban Sustainability Problems

Here we present some of the common fundamental principles of data science underlying the above-discussed types of data mining tasks. Provost and Fawcett (2013) provide a detailed overview of the fundamentals of data science and data mining, in particular how they allow to think about problems within the business domain where data mining may be brought to bear. This overview entails a lot of common aspects that apply to the urban domain as well. However, as mentioned above, a fundamental concept of data science is the process of data mining, which involves relatively well-understood stages entailing the application of ICT tools and methods pertaining to the automated discovery of patterns and correlations from large masses of urban data across distributed environments, as well as creativity, urban sustainability knowledge, and common sense (as to, for example, defining and crafting variables and structuring problems as part of data preparation as a subprocess of the data mining process). In short, data mining involves the application of a considerable amount of science and technology, as well as skills and expert knowledge.

Next, we present a well-understood process of urban analytics that places a structure on the problems pertaining to urban sustainability, allowing reasonable consistency, repeatability, and objectiveness. The derivation and formulation of this data mining process (see Fig. 4.3) is based on cross–industry standard process for data mining (e.g. Kurgan and Musilek 2006; Marbán et al. 2009; Ponce and Karahoca 2009; Chapman et al. 2000; Shearer 2000) and the outcome of the review. The deep technical details of the subprocesses of the data mining process and how they relate to urban domains and sub-domains in the context of sustainability dimensions is beyond the scope of this chapter.

Applicable to the domains of smart sustainable cities (transport, traffic, mobility, energy, environment, health care, education, governance, etc.), this process diagram emphasizes the idea of iteration as the case for all existing codifications of the process of data mining. This implies that solving a particular urban sustainability problem may require going through the process more than once. The entire process is an exploration of the urban data and how it can be integrated. Thus, the rationale for the iteration is for the group of data scientists (or urban analysts) to increase their understanding and thus gain more knowledge as they explore the problem and devise the right solution to it. Indeed, after the first iteration, the process becomes well-informed and revealing. Let us now discuss the steps in more detail.

4.5.1 Urban Sustainability Problem Understanding

Initially, it is crucial to understand the urban sustainability problem that is to be tackled, that is, to ask the right or relevant question to go about exploring or investigating. This is not an evident or clear-cut thing per se. Sustainability endeavors within diverse urban domains and how they relate to physical, environmental, social, and economic dimensions of smart sustainable cities hardly ever come pre-packaged as unambiguous or straightforward data mining problems. Usually, recasting the problem (present or organize it in a different approach) associated with one or more dimensions of urban sustainability and devising an acceptable solution is an iterative (nonlinear) process of discovery taking the form of cycles within a cycle, as illustrated in Fig. 4.3. The initial formulation of any urban sustainability problem is unlikely to be complete, thereby the need and relevance for multiple iterations to achieve an adequate, or ideally optimal, solution formulation. The understanding stage of the urban sustainability problem represents part of competence and skillfulness where the urban analysts or specialized data scientists' creative and innovative ideas become determining in the process of problem formulation with regard to how to cast the urban sustainability problem as a set of data science problems. In the domain of urban sustainability, both specialized and interdisciplinary knowledge help urban analysts come up with novel problem and solution formulations.

There are a wide variety of powerful techniques to apply and combine to solve particular data mining problems associated with urban sustainability dimensions in relation to various domains of smart sustainable cities. They are introduced and exemplified in the previous section. Typically, the early stages of any problem in

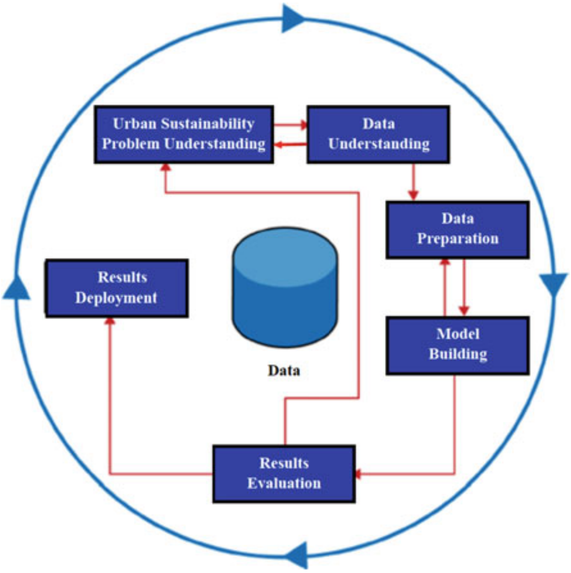


Fig. 4.3 The data mining process applied to urban sustainability problems

this regard entail designing a solution that takes advantage of these techniques. This can signify engineering the urban problem in ways that consist of one or more subproblems that involve building clusters or constructing models for classification, probability estimation, regression, and so forth.

To understand the urban sustainability problem as a first stage, the urban analysts who are in charge of structuring the problem should think carefully about the use scenario. Provost and Fawcett (2013) devote two entire chapters (Chaps. 7 and 11) to this concept, which is one of the most important concepts of data science. The understanding stage involves understanding the project objectives and requirements from an urban sustainability perspective, converting this knowledge into a data mining problem definition, and creating a preliminary plan to achieve the objectives. That is to say, based on the concept of use scenario, what exactly we want to carry out, how exactly we would carry it out, what aspects of use scenario constitute possible models of data mining, and which kind of models are most relevant. As to the latter case, the way forward is to begin with a simplified view of the use scenario (e.g., traffic light control, energy demand management, car sharing implementation, etc.). As the process will evolve, we will loop back and adjust the use scenario to better reflect the actual urban need. This entails framing an urban sustainability problem in ways that can allow us to systematically and effectively decompose it into data mining tasks. In fact, "a critical skill in data science is the ability to decompose a data analytics problem into pieces such that each piece matches a known task for which tools are available. Recognizing familiar problems and their solutions avoids wasting time and resources reinventing the wheel. It also allows people to focus attention on more interesting parts of the process that require human involvement—parts that have not been automated, so human creativity and intelligence must come into play." (e.g., Provost and Fawcett 2013, p. 20) In relation to urban sustainability use scenarios, several environmental, social, and economic indicators could be extracted from historical urban data, assembled into predictive models (associated with mobility, travel, traffic, energy, health care, education, utility, and so on), and then deployed in the operating and organizing urban processes and activities as part of data-centric applications spanning a variety of urban domains in relation to the operational functioning, management, and planning of smart sustainable cities. In this regard, the predictive model constituting an aspect of a particular use scenario in this respect abstracts away most of the complexity of the urban world, focusing on a specific set of environmental, social, or economic indicators that correlate in some way with the value of the target variable to be predicted. For example, an environmental urban sustainability problem would be to find out if a group of dwellers will be environmentally sustainable. A subtask of data mining that will likely be part of the solution to such a problem is to estimate from historical data the probability of dwellers being environmentally sustainable in a district characterized by certain typologies and design concepts on the basis of a set of descriptive attributes entailing different environmental and spatial indicators. The resulting predictive model (patterns and correlations) could then be used as insights in sustainable urban strategies or planning practices.

4.5.2 Data Understanding

In this stage, the focus is on matching the problem with the data, a process that involves understanding the strengths and weaknesses of the available data. In this regard, the solution to the urban sustainability problem as a goal is to be built from the available raw material. Historical urban data often are collected and stored for purposes unrelated to the current urban problem, or sometimes for no explicit purpose at all. Different databases are available across diverse urban domains and owned by different urban entities, covering different information on citizens, transactions, movements, observations, and so on, and may have varying degrees of reliability, different formats, and varied costs. In the urban domain, some data are open and thus accessible to the public for use while other data are confidential and hence pose privacy issues. Also, some data are available virtually for free while other data require effort to obtain or even need to be acquired. Still not all the data needed for building solutions to a given urban sustainability problem exist. Hence, some data are likely to necessitate entire ancillary projects (providing necessary support to the primary activities or operation of the involved urban stakeholders) as organizations, institutions, and enterprises to arrange their collection and storage.

In the context of smart sustainable cities, it is necessary to put in place a cross-service domain system to ensure that access to the data from different urban domains is available at all times in terms of data input and result visualization by the different urban entities involved in the domain of sustainability planning. Prior to this, it is important to ensure that the diverse kinds of datasets pertaining to the areas associated with urban sustainability (traffic, energy, environment, mobility, health care, etc.) are open for use by the city constituents with respect to big data applications in relation to operations, functions, services, designs, strategies, practices, and policies.

Furthermore, data warehousing is of critical importance in terms of data understanding. It serves to collect and coalesce data from across urban systems involving multiple urban entities (e.g., departments, authorities, institutions, enterprises, etc.), each with a set of its own databases. The purpose is to enable various analytical systems across urban domains to have access to the central data warehouse. Residing usually at a single site, a data warehouse is a massive repository of information collected from multiple sources but stored under a unified schema. In this regard, data warehousing can be regarded as a facilitating technology of data mining in the context of smart sustainable cities. This relates to such data mining models used to perform data processing and analysis functions as distributed data mining, grid-based mining, or data mining from multi-technology integration. While it not always necessary in other domains such as business and industry because most data mining does not access a data warehouse, it is very necessary in the domain of urban sustainability. Indeed, smart sustainable cities rely on or decide to invest in data warehouses or storage facilities so that they can apply data mining more broadly and deeply. For example, if a data warehouse integrates records from travel behavior, energy consumption as well as from traffic system and mobility patterns, it can be used to find characteristic patterns of effective typologies and design concepts in terms of urban planning and design (see Bibri and Krogstie 2017b).

A critical part of the data understanding stage in the context of smart sustainable cities is estimating the costs and benefits of data sources and data repositories and deciding whether further effort is merited, in particular, in relation to the investment associated with the collection, storage, and processing of urban data. In relation to data warehousing and processing, urban data do require additional effort to be collated after all datasets are acquired and accessible and to be mined. As data understanding progresses in relation to attempting to solve various urban sustainability problems, solution paths may change direction and new insights come into play in response, and the efforts of urban analysts may even fork, as sometimes one problem may have different solutions, or two problems of the same concern may be categorized significantly different in the sense that these problems may require unsupervised approaches, such as classification, regression, and probability estimation or profiling, clustering, and co-occurrence grouping. It is important, when attempting to understand data, to dig beneath the surface to uncover the structure of the urban sustainability problem in terms of what analytical tasks are of more relevance to solving that problem, as well as the data that are available. And subsequently, we come to match these data to relevant data mining tasks for which there are substantial scientific and technological methods and systems to apply. It is not unusual for an urban sustainability problem, whether be it physical, environmental, economic, or social, to contain several data mining tasks, often of different types, whose solutions should be integrated for effective outcomes (see Chap. 11 from Provost and Fawcett (2013) for more detail).

In sum, data understanding encompasses the following steps:

- Data collection and warehousing,
- Familiarity with the data,
- Identification of data quality problems,
- Discovery of first insights,
- Detection of interesting subsets, and
- Formation of hypotheses for hidden information.

4.5.3 Data Preparation

The analytic techniques to bring to bear as to solving urban sustainability problems impose certain requirements on the data they employ. They require the data be in a certain form, which often is different from how the data are provided originally or naturally and collected automatically. Thus some conversion of the data into suitable forms is necessary in order to be able to achieve better outcomes. Typical examples of data preparation in the urban domain entail coordinating data from different sectors by bringing the different elements of urban entities or complex activities into a relationship that will ensure efficiency or harmony (e.g., data from transport, traffic, and environment departments), converting data to tabular format, combining tables with similar or shared attributes, inferring or completing missing values, removing repetitive values, and converting data to various types for consistency. Concerning the latter, some data mining techniques are, as discussed above, designed for categorical data (e.g., for classification) while others deal only with numerical values (e.g., for regression), which must often be normalized so that they become computationally comparable and yield the desired results. The interested reader can be directed to Chap. 3 from Provost and Fawcett (2013) for a detailed discussion of the most typical format for mining data and rules of thumb for doing such conversions. In fact, data preparation techniques could be the topic of a whole book by themselves.

A related aspect of conversion, which pertains to the early stages of the automatic processing of the data, is to provide guidelines on how all the different cross-thematic data categories can be integrated. More generally, urban analysts team may spend considerable time early in the process defining and crafting the variables used later in the process as part of structuring the urban sustainability problem, an aspect that has a lot to do with expert knowledge (urban sustainability) as well as creativity and common sense. Overall, data preparation entails constructing the final dataset to be fed into the data mining algorithms, where tasks encompass tables, records as well as attribute selection, data transformation, and data cleaning.

4.5.4 Model Building

Generally speaking, a model is an (over)simplified view of the real world or a representation of reality created to serve a purpose. In the context of smart sustainable cities, this oversimplification is based on assumptions about what is and is not important for the purpose of advancing their contribution to the goals of sustainable development in relevance to diverse urban domains, or sometimes based on constraints on information or tractability. The output of modeling in the process of data mining is some sort of patterns capturing regularities in the urban data. These data pertain to different urban domains and hence typify travel behavior, mobility form, energy consumption, land use, network performance, service delivery, facility accessibility, and so on. It is during modeling when data mining techniques are applied to the data through building models from both historical and real-time data depending on the urban sustainability problem that is to be solved. In this regard, it is crucial to have some understanding of the sorts of available techniques and algorithms as part of the fundamental ideas of data mining, which are discussed and exemplified in the previous section. In this stage, the urban analysts ensure various data mining techniques and algorithms are selected and applied in relevance to the urban sustainability problem and parameters are learned. Also, some methods may have specific requirements on the form of input data, and, therefore, going back to the data preparation stage may be needed.

There are mainly two types of modeling in data mining based on supervised and unsupervised learning methods: predictive data mining and descriptive data mining, respectively. Predictive data mining generates models described by particular urban data (from mobility, travel, traffic, utility, education, health care, well-being, and so on) and uses some variables, with important, informative gains, in the dataset to predict future or unknown values of target variables. Speaking of informative gains and in relation to supervised segmentation, finding important, informative variables in the dataset pertaining to the entities described by the data as one of the fundamental ideas of data mining means the variables that are most predictive of the target, or alternatively, have the best correlation with the target. While for variables to be informative usually varies among applications, underlying informativeness is the idea that information generally represents a quantity that reduces uncertainty about something in the sense that the better the information provided, the more the uncertainty is reduced by that information. Having a target variable crystalizes the idea of finding informative attributes with regard to identifying whether there are one or more other variables (or finding knowable attributes that correlate with the target of interest) that reduces the uncertainty about the value of the target or in it. Determining these correlated variables is intended to provide key insights into the urban sustainability problem on focus.

Commonly, prediction signifies forecasting a future event. A predictive model is a formula (mathematical or logical statement but usually hybrid of the two) for estimating the future or unknown value of the target. This implies that this value could be something in the future, in the present, or in the past. Indeed, in the urban domain, data mining may deal with historical or real-time data, and hence models are built and tested using events from the past and present. Now we exemplify predictive modeling for illustrative purposes. We can think of many urban questions involving predictive modeling, such as how can we segment the citizens with respect to mobility as something that we would like to predict or estimate in relation to a particular spatial scale (e.g., district, city, and region). The target of this prediction can be something we would like to relate to environmental sustainability or social sustainability, such as which individual movements are likely to increase emissions and which ones are likely to be influenced by existing typologies and design concepts across a particular spacial scale, or which individual movements are likely to be associated with enhanced spatial accessibility to services and facilities as an aspect of the quality of life. In this regard, the target might be cast in a negative or positive light. As explained in the previous section, a predictive model (based on such data mining tasks as classification, regression, and/or probability estimation) focuses on estimating the value of some particular target variable of interest. To extract patterns from data (useful knowledge pertaining to mobility) in a supervised manner entails segmenting the citizens dwelling in a particular district into subgroups with instances of similar values for the target variable as part of subgroups that have different values for the target variable. In this case, the segmentation is performed using values of variables that are known when the target variable is not in order to predict its value accordingly. In addition, the segmentation may concurrently provide a human-understandable set of segmentation patterns. An example of a segment expressed in English would be: "people who live in density and mixed land-use-oriented areas and prefer walking and cycling on average have an emission rate of 5%." Specifically, 5% describes the predicted value of the target variable for the segment whose definition (which references some particular attributes) is "people who live in density and mixed land-use areas and prefer walking and cycling."

As regards to descriptive data mining, it produces new, nontrivial characteristic or grouping information based on the available urban dataset (e.g., life quality, travel behavior, mobility, accessibility, network performance, land use, transport, etc.) while focusing on finding patterns for human interpretation. In descriptive modeling, the primary purpose of the model is to gain meaningful insights into the underlying phenomenon of urban sustainability. A descriptive model of citizen travel behavior or mobility mode would tell us what citizens who use sustainable transport or cycling and walking typically look like. A descriptive model must be judged in part on its intelligibility and easiness of understanding for an effective deployment in relation to urban services, designs, strategies, or policies, in contrast to a predictive model which may be assessed solely on the basis of its predictive performance determined by previous experience (training data). As some of the same techniques and algorithms can be used for both descriptive and predictive modeling, the difference between supervised and unsupervised data mining models is not as strict as this may imply, as hinted at in the previous section.

4.5.5 Results Evaluation

After building the desired models (or patterns capturing regularities in the data), it is important to assess the data mining results rigorously and to gain confidence that they are valid and reliable before moving on in the process. This is what the evaluation stage is about. It is desirable to have confidence that the generated models represent true regularities and not just sample anomalies, odds, or idiosyncrasies. The underlying assumption is that an urban analyst can always find patterns by looking hard enough at any dataset, but these patterns may not survive careful scrutiny, which is one of the fundamental concepts of data science: overfitting. Hence, it is inadvisable to deploy the results of data mining immediately as to their use for decision-making purposes. Prior to their deployment, results have to be evaluated in ways that ensure the generated models satisfy the original urban goals in terms of supporting decision-making or making decisions with regard to improving some aspect of sustainability in the context of smart sustainable cities. This involves finding a data-analytic solution to the urban sustainability problem being explored. A data mining solution (model) often is only a piece of the larger solution to the urban sustainability problem in question. And it needs to be evaluated as such. There are different external factors that should be taken into account when evaluating models, which might make them impractical, although they pass strict evaluation tests in a controlled laboratory setting.

Given the complexity and scale of urban sustainability projects and what this entails in terms of the various urban stakeholders that can be involved. The stakeholders have interests in the urban sustainability decision-making that will be supported by the resultant models. This implies that the results of data mining are to be evaluated using both qualitative and quantitative metrics. However, the stakeholders need to be satisfied by the outcome of the evaluation with regard to the quality of the models' decisions in order to be "sign off" on the deployment of the resultant models. Irrespective of the domain application of urban sustainability in this context, the basic idea guiding this quality is to ensure the model is unlikely to make mistakes or to be useless in directing urban operations, functions, services, designs, strategies, practices, and polices in line with the goals of sustainable development. To facilitate this kind of qualitative evaluation, the urban analyst must think about the comprehensibility of the model to urban stakeholders, and accordingly attempts to find ways to render the behavior of the model comprehensive, if the latter happens to be not so due to some complex mathematical formula, for example. The rationale for performing the evaluation early on to provide a comprehensive assessment framework before its use (production) is that it may be difficult to obtain detailed information on the performance of a deployed model due to the limited access to the production environment where such model is applied. Adding to this is that the model may be deployed as part of decision-making systems related to diverse urban domains. Moreover, deployed systems (e.g., related to urban operations, functions, services, strategies, designs, practices, and policies) typically contain many parts that they tend to move around in the underlying system, and assessing the contribution of a single part of the system is difficult. To obtain the most realistic evaluations before taking the risk of deploying the resultant models in urban systems and domains, it is recommended to build testbed environments that can reflect production data as closely as possible. The technical details of how to do so, as well as to design advanced experiments for instrumenting deployed systems for evaluations to ensure that some external factors or urban dynamics are not changing to the detriment of the model's decision-making, are beyond the scope of this chapter. The interested reader could turn to Kohavi et al. (2012) for some insights. In addition, for a detailed of system design to help deal with other evaluation-in-deployment issues (e.g., change to input data as to format and substance), the reader can be directed to Raeder et al. (2012). In sum, the evaluation stage requires current model should have high quality from a data mining perspective, and before final deployment, it is important to test whether the model achieves all urban sustainability project objectives.

4.5.6 Results Deployment

By mining the big data of smart sustainable cities, it is possible to discover new or advanced principles of urban sustainability planning as well as urban changes. This development will allow an inference of the urban systems and domains' performances based on, and in response to, new operations, functions, designs, strategies, practices, and policies and various other aspects in the context of urban sustainability. This is what the deployment of the results of data mining is about from a general perspective. In the deployment stage, the results of data mining are put into real use in terms of making, supporting, or automating different kinds of decisions associated with urban operational functioning, planning, and service delivery. These aspects of smart sustainable cities concern in turn diverse urban systems and domains. The clearest cases of deployment in this regard entail implementing predictive or descriptive models in processes operating and organizing urban life (traffic, transport, energy, etc.) or information systems associated with public services (health care, education, safety, utility, etc.). In this context, a model for predicting travel behavior could be used in public transport system engineering or management. For example, travel "data are potentially extremely useful for figuring out disruptions on the [transport] system. We do need, however, to generate some clever cognitive analyses of how people make their way through the various transport systems, just as we need to assign travelers to different lines to ensure that we can measure the correct number of travelers on each line… The state of the art in what we know about navigation in complex environments is still fairly primitive. Many assumptions have to be made and we have no data on what different users of the system have actually learned about their routes. New users of the system will behave differently from seasoned users and this introduces further error. We can see disruption in the data by determining the times at which travelers enter and exit the system, but to really predict disruption on individual lines and in stations, we need to match this demand data to the supply of vehicles and trains that comprise the system." (Batty 2013, p. 278) Many other kinds of models can be built into environmental systems, transport systems, energy systems, water distribution systems, communication systems, building systems, traffic systems, and a wide variety of service-oriented information systems (utility, health care, education, safety, etc.) to increase the contribution of smart sustainable cities to the goals of sustainable development in terms of environmental regeneration, economic efficiency, and social equity and well-being. The data mining techniques themselves can be deployed in the urban domain, rather than the models produced by a data mining system, due to the fact that smart sustainable cities are highly complex and dynamic systems that can evolve faster than the data scientists specialized in urban analytics can adapt.

Deployment can also be much less technical when a set of rules discovered by data mining techniques could help to quickly diagnose and fix a common error in some systems (spatial organization, typology, bicycle or car sharing approach, etc.). In this case, the deployment can be in the form of disseminating new practices containing the rules in question. Deployment can, moreover, be much more subtle, such as a change to services, operations, and strategies resulting from insights gained from mining the urban data.

Results deployment often returns to the urban sustainability problem understanding phase, irrespective of whether it is successful. The process of data mining generates a great deal of insights into the urban sustainability problem as well as the difficulties surrounding its solution, which can be mitigated by a second iteration. This is to enhance the solution through new ideas for improved performance, an endeavor that usually emanates from the experience of thinking about the urban data and the performance goals of urban systems and domains in terms of their contribution to the goals of sustainable development. Important to note is that starting the cycle again of data mining is not necessarily related to the failure of results deployment. The stage of evaluation may reveal that the resultant models are suitable for deployment, thereby the need for adjusting the problem formulation or obtaining new, different data. This is illustrated in the process diagram (Fig. 4.3): the link from results evaluation back to urban sustainability problem understanding.

To sum up, it is worth pointing out that in urban analytics, it is critically important for urban analysts to be able to formulate urban sustainability problems well in relevance to each urban domain (e.g., traffic system management) and sub-domain (e.g., traffic light control), to prototype (analytical) solutions quickly, to make realistic assumptions in the face of ill-defined and structured problems, to design scientific procedures for making meaningful discoveries, and to analyze results. These qualities necessitate seeking and building a strong data science team with specialized expertise and interdisciplinary knowledge rather than traditional software engineering professionals. In light of this, new partnerships and alliances among different urban entities are necessary for the use of big data analytics in the context of smart sustainable cities, especially city authorities are likely to lack data scientists and hence must borrow them from academic institutions and industrial organizations. Also, to facilitate data science, more data scientists are to be acquired by diverse urban departments. Otherwise, novel tools are needed for translating big data into easily understandable analytical approaches so that data analysts within urban sustainability can handle data by running predefined forms of analytics.

4.6 Applications of Data Mining for Urban Sustainability Analytics

There are emerging empirical applications of data mining to the systematic study of smart sustainable cities and the associated problems pertaining to different dimensions of sustainability. The data deluge holds great potential for advancing urban sustainability in the years ahead. The coupling of big data analysis and computational modeling and simulation can open new horizons for the analysis of urban systems in the context of sustainability. Below is a set of selected data mining applications for urban analytics in relation to diverse urban domains.

4.6.1 Energy Management

Zhao et al. (2016) discuss the energy consumption data with the parameters—public building, structure, construction, and behavior pattern. They compare traditional methods and data mining process for energy consumption analysis. The focus is on the use of data mining techniques for efficient utilization to obtained knowledge. The attempt is to fill that gap by utilizing data mining in the energy efficiency evaluation of buildings. In their paper, Zhou et al. (2016) address big data driven smart energy management in terms of how to turn big data to big insights through advanced analytics. They propose the process model for smart energy management, and also provide insights into data collection, integration, processing, sharing, and security.

4.6.2 Healthcare

Milovic and Milovic (2012) address various issues related to health care. Data mining in health care aids in organizing large amount of data, use ICT for automation, maintaining the security, conducting early diagnosis, predicting the trend, and the analysis from various perspectives. They further suggest the classification and regression, association rule, cluster analysis, and text mining techniques for analysis of healthcare data.

4.6.3 Water Management

Khan et al. (2012) compare the effectiveness and performances of several data mining techniques such as decision tree, regression in predicting irrigation water demand. The study compares SysFor with other classification techniques for the first time with accuracy and efficiency.

4.6.4 Education

Sin and Muthu (2015) highlight the challenges and issues facing education, including performance prediction in learning, predicting future failures and finding solutions, designing courseware, assessment, and research. They suggest the use of different open source tools, such as MongoDB, Hadoop, and Orange.

4.6.5 Mobility

Benevolo et al. (2016) discuss six objectives of mobility in the context of smart cities, namely pollution, traffic blocking, people safety, noise pollution, transfer speed, and transfer cost. They suggest four key factors: public companies, private companies, local government agencies, and the integration of these three that is Integrated Transport System (ITS). They propose some innovative solutions such as the use of ICT for smartphone-based integrated ticketing system, car sharing, and car reservation. In addition, the authors focus on ICT based ITS which includes video surveillance for security, traffic control, and traffic data collection system.

4.7 Answering Examples of Urban Sustainability Questions Using Different Big Data Analytics Techniques

There are other analytics techniques that might be applied in the domain of urban sustainability, which go beyond this chapter's scope in terms of the principles of extracting useful knowledge from urban data, including statistics, regression analysis, machine learning, and database querying. Provost and Fawcett (2013) provide a descriptive account of these techniques in terms of their goals and role, as well as draw comparisons and contrasts with data mining. The main difference between data mining technique and the other analytics techniques is that the former focuses on the automated search for or extraction of useful knowledge or patterns from data. While data mining differs from these analytics techniques, it remains complementary to them; however, the boundaries between the two are not always sharp (Provost and Fawcett 2013).

Urban analytics involves the application of various techniques to the analysis of urban data depending on the nature of the urban problem that is to be solved in relation to environmental, economic, and social dimensions of sustainability. Hence, it is useful to be acquainted a bit with these techniques in the context of smart sustainable cities to understand what their objectives are and when they can be applied. To illustrate how these techniques apply to urban analytics, we consider a set of questions pertaining to urban sustainability that may arise while ensuring that they are related but subtly different, and the techniques that would be appropriate for answering them. Of particular importance here is to understand these differences in order to understand what techniques are more suitable to be employed in the data mining process.

1. Who are the most environmentally sustainable citizens in terms of mobility mode, travel behavior, and household energy consumption in the different districts of a smart sustainable city?

If "environmentally sustainable" can be defined clearly based on different existing datasets yet sharing relevant attributes, this is a straightforward database query. A standard query tool could be used to retrieve a set of citizen records from a data warehouse or a database combining such datasets according to each district. The results could be sorted by mobility forms (cycling, walking, automobile, etc.), frequently used public transport means, and cumulative energy consumption amount, or some other operational indicators of environmental sustainability.

2. Is there really a difference between the environmentally sustainable citizens and the average citizen in a smart sustainable city?

This is a question about a hypothesis. In this regard, there is a difference in value to the city authority between the environmentally sustainable citizens and the average citizen in a smart sustainable city. Here statistical analysis can be used to derive a probability bound that the difference is real (e.g., household energy consumption compared to other environmental indicators), and statistical hypothesis testing can be employed to confirm or disconfirm the difference in question. Regarding the probability, an example of the outcome would typically be: the value of these environmentally sustainable citizens is significantly different from that of the average citizen, with probability estimated to less than, for example, 6% that this is due to random chance.

3. But do these citizens fall under certain groups and how can they be characterized (and who are they)?

Here the intent is to describe common features (provide characteristic information) of environmentally sustainable citizens, thereby attempting to do more than just listing them out. The characteristics of individual citizens can be extracted from a data warehouse or an extended database using database querying, which also can be used to generate summary statistics. But using clustering as a data mining technique would signify a rather deeper analysis in terms of determining what characteristics (automated pattern-finding) differentiate environmentally sustainable citizens from non-environmentally sustainable ones.

4. Will some particular new citizens be environmentally sustainable in one of the districts of a smart sustainable city? How much household energy saving should these citizens be expected to achieve?

These questions could be addressed by classification and regression, respectively, as data mining techniques that examine historical citizens' records and produce relevant predictive models involving the aforementioned environmental indicators as attributes or features. These predictive models could then be applied to new citizens to generate estimations.

The data mining process is useful as a framework to urban analysts for examining a data mining proposal related to various kinds of urban sustainability problems. And it provides a set of questions that can be asked about that proposal to aid in understanding whether it is well conceived or is fundamentally flawed.

4.8 Knowledge Discovery in Databases (KDD) and Related Issues

4.8.1 Understanding the Process of KDD and Illustration of Its Key Steps

Data science involves scientific systems, processes, and methods to extract useful knowledge from large masses of data in various forms, including KDD. KDD refers to the broad and nontrivial process of discovering useful knowledge in data, i.e., identifying hidden, implicit, unsuspected, valid, novel, previously unknown, meaningful, potentially useful, and ultimately understandable patterns in data. It involves such subfields of computer science as machine learning, pattern recognition, database systems, statistics, artificial intelligence, and data visualization. Thus, KDD is an interdisciplinary area that focuses on methodologies for extracting useful knowledge from data. These methodologies are becoming increasingly immensely needed due to the rapid growth and proliferation of urban data and the extensive use of databases in diverse urban domains (e.g., mobility, traffic, transport, energy, utility, health care, education, safety, etc.), as we will exemplify below in relation to mobility data. KDD as a process is depicted in Fig. 4.4 and consists of an iterative sequence of the following steps:

Prior to selection, urban data are collected, stored, and integrated (combination of multiple data sources). These techniques are performed on the data contained in databases, data warehouses, or other data repositories.

1. Data selection involves retrieving the relevant data from the database or data warehouse for the analysis task. Creating a target dataset entails focusing on a subset of variables or data samples, on which knowledge discovery is to be performed. The database or data warehouse server fetches the relevant data on the basis of the data mining request.
2. Preprocessing involves collecting necessary information to account for noise as well as handling missing data fields through de-noising, filtering, fusing, and

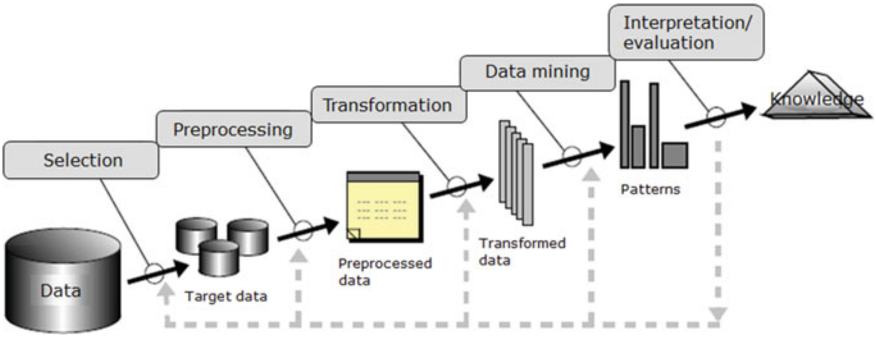


Fig. 4.4 The Process of Knowledge Discovery in Databases (KDD). *Source* Fayyad et al. (1996)

standardizing, thereby removing redundant, unnecessary, and irrelevant data. This is to make the dataset ready for processing.

3. Data transformation is about data reduction and projection, that is, finding useful features/attributes to represent the data depending on the objective of the data mining task being performed and using dimensionality reduction to decrease the effective number of variables under consideration. In other words, the data in this stage are consolidated into forms relevant for mining by performing summary operations.
4. Data mining is where the data mining task is selected in order to build models (decision tree, neural network, linear or nonlinear equation, etc.) or to search for patterns of interest in the data in a particular representational form based on the algorithms being applied, in addition to deciding which models and parameters may be appropriate and matching the applied data mining algorithms with the overall criteria of the whole process.
5. Patterns evaluation entails assessing the data mining results and gaining confidence that the resultant models are valid and reliable, e.g., identifying the truly interesting patterns capturing regularities in the data and not just sample anomalies, odds, or idiosyncrasies. In other words, the identified patterns should represent knowledge based on some interestingness measures according to the domain knowledge used to assess the interestingness of the resulting patterns. In employing interestingness thresholds or constraints, the step interacts with the data mining module (or may access such thresholds or constraints stored in the knowledge base) in order to focus the search toward interesting patterns. In knowledge presentation, visualization techniques are used to present the mined knowledge in an understandable format for human interpretation. This entails graphical user interfaces between the data mining system and the data analyst to allow them to interact with each other for different kinds of simple and complex tasks, including carrying out exploratory data mining, browsing database and data warehouse schemas, and visualizing the mined patterns in different forms.

In all, to make the decision on what qualifies as useful knowledge with regard to decision-making pertaining to sustainability aspects in the context of smart sustainable cities, KDD involves carefully choosing variable selection mechanisms, encoding schemes, preprocessing, reductions, and projections of the data prior to discovering the intended patterns and building the relevant models as well as their evaluation, interpretation, and visualization.

4.8.2 Overlaps and Commonalities Between Data Mining and KDD Processes

KDD overlaps with data mining in that it emphasizes the high-level application of particular techniques and algorithms of data mining. This implies that data mining refers to the application of these techniques and algorithms for extracting

Table 4.1 The link between data mining and KDD processes

The data mining process	The knowledge discovery process
Data understanding	Selection
Data preparation	Selection, preprocessing, and transformation
Model building	Data mining
Results evaluation	Interpretation/evaluation

patterns and building models from data without the additional steps of the process of KDD. Accordingly, data mining is simply an essential step in the process of KDD, as illustrated in Fig. 4.4. However, the process of data mining and that of KDD have been used interchangeably, and, therefore, it is deemed important to illustrate how the two converge on most of the stages for extracting useful knowledge from data. For example, the selection step in KDD includes developing an understanding of the application domain, the relevant prior knowledge, and the objectives of the project. These represent the urban sustainability problem understanding phase of the process of data mining. Table 4.1 illustrates the link between the process of data mining and that of KDD.

4.8.3 A Holistic System in Support of the Process of KDD for Urban Sustainability

In the quest to grasp the complexity of the process of KDD in the context of smart sustainable cities, it is necessary to develop an entirely new holistic system that integrates data collection, mining, querying, and visualization. The entire process of KDD able to create the needed knowledge for enhanced decision-making and insights as services associated with different dimensions of sustainability should be expressible within applications across diverse urban domains that support the following steps (Batty et al. 2012, p. 497), to summarize the aforementioned steps with some additional ones:

- The acquisition of data from multiple distributed sources…
- The management of data streams;
- The integration of heterogeneous data into a coherent database;
- Data transformations and preparations;
- Definition of new observables to extract relevant information;
- Methods for distributed data mining and network analytics;
- The management of extracted models and patterns and the seamless composition of patterns, models, and data with further analyses and mining;
- Tools for evaluating the quality of the extracted models and patterns;
- Visual analytics for the exploration of behavioral patterns and models;
- Simulation and prediction methods built on top of the mined patterns and models; and

- Incremental and distributed mining strategies needed to overcome the scalability issues that emerge when dealing with big data.

A preliminary, partial example of this line of research already exists in the domain of mobility (e.g., Giannotti and Pedreschi 1998) in relation to smart cities of the future (e.g., Batty et al. 2012). This is also of relevance to smart sustainable cities of the future (Bibri and Krogstie 2017b), which is becoming increasingly an exemplar for encompassing all the domains of such cities (e.g., traffic, transport, energy, land use, health care, education, network performance, and environment) in terms of data, patterns, and models, as well as their amalgamation in the context of sustainability. This is a continuing research challenge for ICT of the new wave of computing (Bibri and Krogstie 2017b).

4.8.4 The Need for Coordination: Database Integration and Domain Networking

The organization and connection of the different components and entities of smart sustainable cities as a complex system entailing a set of dynamic and intertwined processes so as to enable them to work together effectively for achieving the goals of sustainable development require huge efforts at database integration and domain networking. Database integration, coupled with domain networking, is at the core of the very early stage of the process of KDD. The unifying goal of this process is to extract useful knowledge from data in the context of large (distributed and heterogeneous) databases. Databases are important to store, manage, and maintain data. They come in various forms, such as graph-databases, document-oriented databases, and relational databases. There are numerous databases to deal with in the realm of smart sustainable cities, and they pertain to diverse urban domains and sub-domains and to the way these may interrelate and collaborate in the context of sustainability. This relates to data warehousing, a process that serves to collect and coalesce data from across the domains of smart sustainable cities involving multiple entities (e.g., departments, authorities, institutions, enterprises, etc.), each with a set of its own databases, to reiterate.

However, to make sense of the growth and proliferation of data in the context of smart sustainable cities, it is necessary to establish standards for database integration and domain networking. Also, new research endeavors should be directed toward advancing database integration and domain networking to improve the performance of urban analytics for enhancing decision-making and insights in relation to urban operations, functions, services, designs, practices, and policies, with the ultimate aim of improving the contribution of smart sustainable cities to the goals of sustainable development. Databases pertaining to urban domains should be integrated and forged using novel and advanced forms of database design and architecture distributed at and adapted to the citywide scale. This requires adopting new tools and methods for capturing data through digital sensing, the automated recording of movements and activities in the urban environment, monitoring interactions in various spatial and temporal settings across the city, and mining online transactions (Batty et al. 2012; Wang et al. 2011). Moreover, much of urban data are inherently networked due to the close collaboration among urban domains (e.g., transport, mobility, energy, environment, and land use) in terms of operational functioning and planning, especially in the context of sustainability. Hence, integrating databases from across a network of urban domains as an arrangement of intersecting horizontal and vertical lines crossing a large number and variety of relevant sub-domains is key to making sense of and effectively and efficiently utilizing big data for extracting useful knowledge to support decision-making in terms of catalyzing and boosting sustainable development processes. New specialized techniques and sophisticated methods for database integration based on network analysis and distributed computing in terms of hardware systems and software applications are necessary, as this is central to collective decision-making and what it entails in terms of data processing and management as well as intelligence functions pertaining to the optimization of the efficiency of energy systems, transport and communications systems, service delivery, and so forth. Accordingly, such functions, which can evolve to take the form of innovation laboratories to allow for monitoring, understanding, analysis, and planning of smart sustainable cities to improve their contribution to the goals of sustainable development, should go beyond the routine and constrained systems (e.g., traffic system management). In all, realizing smart sustainable cities as a techno-urban vision requires dedicated efforts at database integration and domain networking in relevance to sustainability.

4.9 The Role of Big Human Mobility Data in the Next Wave of Urban Sustainability Analytics

4.9.1 Mobility Knowledge Discovery and Its Use in Relation to Sustainable Urban Forms

One of the fundamental ingredients for the next wave of urban analytics that is rapidly gaining momentum is large datasets pertaining to human mobility, fostered by the ubiquity presence or widespread diffusion of sensor, data processing, cloud computing, and wireless communication technologies. These technologies, as a by-product of their normal operation, allow for collecting, coordinating, processing, and analyzing colossal repositories of spatiotemporal data representing citywide proxies for human mobile activities, as well as physical objects movements associated with individual and collective mobility. The massive data repositories pertaining to human mobility will be one of the determinants of the future form of urban analytics and hence urban planning and development practices, e.g., understanding the links between individual and collective human mobility and city structures and forms on the basis of big data analytics and related simulation models. This entails analyzing vast amounts of spatiotemporal data to find meaningful patterns and correlations with respect to the different dimensions of sustainability, as well as building simulation and prediction methods on top of the mined patterns and models. This is of high relevance as to guiding and directing the operational functioning, planning, and design of environmentally, socially, and economically sustainable urban forms. Big mobility data provide a powerful environmental, social, and economic microscope, which can serve to understand human mobility in relation to the typologies and design concepts of sustainable urban forms, and discover the hidden patterns and models that characterize the trajectories urbanites follow during their daily movements and activities in connection with the performance of such forms in the context of sustainability. Thus, new advanced analytical and mining methods for knowledge discovery should be developed for capturing and extracting useful knowledge from sustainability-oriented spatiotemporal data. Thus far, several international projects "have shown how to support the complex knowledge discovery process from the raw data of individual trajectories up to high-level collective mobility knowledge, capable of supporting the decisions of mobility and transportation administrators, thus revealing the striking analytical power of big mobility data." (Batty et al. 2012, p. 488) New projects should, with their evocations, provide a legitimation of extending these capabilities to include other uses of more relevance and meaningfulness, associated with the relationship between such analytical power and urban planning and design areas in the context of sustainable urban forms. There are several high-level concepts that urban analysts in this context can reason about with respect to the so-called sustainable typologies and design concepts, including systematic movement behavior, travel behavior, commuting behavior, energy usage behavior, traffic behavior, accessibility behavior, economic networks, social networks, and so on. Undeniably, big mobility data analytics is, to reiterate, more suitable and effective than traditional data collection and analysis, such as surveys, interviews, participatory and nonparticipatory observations, manual examinations of records, and so on due to their shortcomings pertaining to high cost, bias, uncertainty, incompleteness, infrequent periodicity, quick obsolescence, contextual focus, and inaccuracy (Bibri and Krogstie 2017b). Whereas "automatically sensed mobility data are ground truthed: real mobile activities are directly and continuously sampled as they occur in real time, but clearly they do not have any semantic annotation or context." (Batty et al. 2012, p. 488) As to the issue of the semantic deficiency of big mobility data, a large body of research has started to show that it can be bridged by the size and precision of the data (Giannotti et al. 2007). Several questions of paradigmatic representatives of the urban analysts in the context of sustainable urban forms need to disentangle the huge diversity of individual locations and dynamical tracks to discover aspects characterized by common behavior and purpose (see Giannotti et al. 2011) in relation to different aspects of sustainability. Finding answers to many current questions in this regard is within the ambit of ICT of the new wave of computing but beyond the limits of the current generation of ICT (Bibri and Krogstie 2017b). We consider that future ICT—given the unique foundation of its application on data science and complexity science—will provide us with dramatically more powerful analytical and mining methods that will inform complex problems concerning sustainable urban forms in terms of their environmental, social, and economic performances. New data and advanced analytics can assist in understanding and substantiating whether or not the typologies and design concepts of sustainable urban forms can be regarded an equilibrium system with respect to how dwellers make choices and whether and the extent to which these choices contribute to the goals of sustainable development. The main areas of interest are mobility patterns, spatial and temporal aspects in urban structures and organizations as well as in social and economic network structures, data-driven characterization of urban operational functioning, and behavior and activity identification related to certain typologies across several spatial scales.

The thrust of using big data analytics (particularly the data mining and knowledge discovery processes) as an alternative to traditional data collection and analysis method to investigate a wide variety of urban sustainability problems is the ease and effectiveness with which the automatic urban analytics can be carried out on different typologies and design concepts and their combination and distribution on every spatial scale and over very different time spans, using cutting-edge tools and technologies which can be deployed on a citywide scale for many purposes. In particular, the strategies through which sustainable urban forms can be achieved entail many features of highly pertinent and meaningful correlations with attributes of individual and collective mobility in relation to energy, traffic, transport, travel, climate, and accessibility and other complex urban dynamics and interconnections that are accessible for analytics to determine and evaluate how effectively the contribution of sustainable urban forms can be performed and planned, respectively, with the purpose of strategically enhancing and sustaining the environmental, social, and economic performances of such forms. To put it differently, the topographic, physical, spatial, morphological, behavioral, and ecological facets of the planning and design concepts and principles of sustainable urban forms certainly provide a wealth of information that can be scrutinized and investigated with sophisticated computational and analytical tools and methods to obtain robust results for advancing urban sustainability as well as for finding effective ways of integrating its environmental, economic, social, cultural, and physical dimensions. Such facets include co-location, position, scale, contiguity level, spatial distribution, temporal variability, emission level, interaction intensity, accessibility, and so on. On the basis of these facets together with those of mobility, it is possible to strategically evaluate the contribution of sustainable urban forms to the environmental, social, and economic goals of sustainable development. For example, the availability of massive data collected from mobile communications and networks have enabled the development of realistic and predicative models of human mobility and the empirical validation of social network hypotheses in large-scale settings (Batty et al. 2012), which relates to the social dimension of sustainability being promoted by sustainable urban forms. Big mobility data aid in scrutinizing different spatiotemporal patterns together with the intensity and frequency of social interactions as well as social structures (Batty et al. 2012). In perspective, exploiting and integrating other information sources associated with the typologies and design concepts of sustainable urban forms and coupling them with mobility patterns and social networks is likely to edge toward understanding and studying the evolutionary dynamics of such forms as social spheres and their evolving borders as social structures. This relates to the collective intelligence functions and simulation models that sustainable urban forms may develop in the near future, which is an enormous challenge.

4.9.2 New Systems for Mobility Behavior Discovery in Relation to Urban Sustainability

Advanced or novel systems need to be conceived as frameworks to master the complexity of the mobility knowledge discovery process in connection with different dimensions of urban sustainability in the context of smart sustainable cities. This emerging urban development approach entails a combination of cutting-edge technologies and their applications and different strategies through which sustainable urban forms can be achieved in terms of typologies and design concepts (see Bibri and Krogstie 2017b for a detailed discussion). One solution to suggest in this regard is an integrated querying and mining system, based on the concept of the trajectories the citizens and their objects follow on daily basis across many spatial and temporal scales, i.e., a sequence of time and space stamped locations, sampled from the itinerary of citizens and their objects, whether in relation to certain typologies and design concepts (density, mixed land use, diversity, green space, sustainable transportation, etc.) or in relation to urban environments. Trajectories pertaining to human mobility and physical and digital objects movement can be built from data sensed routinely and automatically in various contexts, including dynamical traces or tracks of different kinds of mobility modes, travel behavior, physical object movement, whether in relation to the typologies and design concepts of sustainable urban forms and their combination across many spatial scales or from a general perspective. Such traces include, and are not limited to, mobile phone call detail records, GPS tracks from vehicular, hand-held navigation devices, and other wirelessly connected everyday objects; time- and space-stamped location records from websites and social media networks; remote sensors for tracking body movements; and social connections and other types of networks. An advanced system can support the complex knowledge discovery process from sensed or captured data of individual trajectories up to high-level collective mobility knowledge, using approaches into, according to Batty et al. (2012, p. 502):

- Trajectory reconstruction from the raw location data;
- Trajectory database management and querying;
- Trajectory mining: pattern extraction, clustering, and prediction/classification; and
- Trajectory visual analytics and model presentation/exploration.

Figure 4.5a, b above show a knowledge discovery oriented analysis performed on a dataset of GPS tracks involving about 20,000 private cars sensed over a 1 week

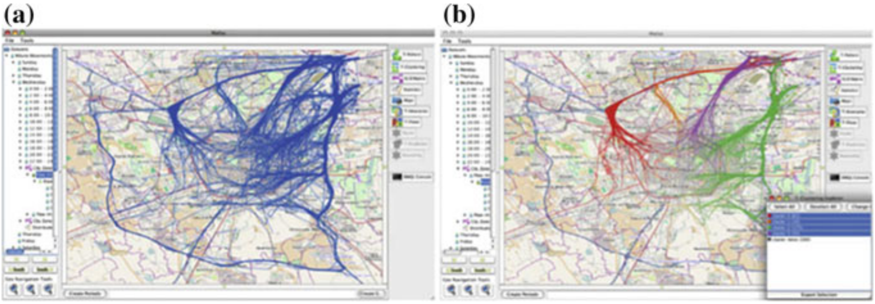


Fig. 4.5 GPS tracks in metro Milan **a** City center and **b** clusters of like trajectories. *Source* Batty et al. (2012)

period of time in the metropolitan area of Milan, Italy. In the example, the clustering algorithm applied on the trajectory of these cars reveals typical profiles and routes of commuting behavior from two selected areas in the city. In the left-hand Fig. 4.5a, the M-Atlas visual interface shows the data pertaining to the trajectories from the city center selected as input for the clustering algorithm, and in the right-hand Fig. 4.5b, the trajectories in the same cluster are visualized by M-Atlas with the same color. In this context, the urban analyst can zoom on the different clusters, studying some aspects of (environmental) sustainability based on different trajectory attributes. Example projects that can be pursued by various stakeholders of smart sustainable cities (authorities, departments, enterprises, etc.) using M-Atlas as enabling technology include the characterization of unsustainable travel profiles on the basis of car use frequency and travel distance, the simulation of a participatory car sharing service, and the preparation of a detailed mobility atlas on the basis of integrated GPS, sensors, participatory mobility data for some urban areas characterized by certain typologies and design concepts as a tool of policy definition and strategy formulation for the public administrations at urban and regional scale (see Batty et al. 2012). Systems as M-Atlas as a map of smart sustainable cities can be extended to other kinds of Atlas that relate to the integrated databases involving various domains in relevance to different dimensions of sustainability.

4.10 Conclusions

We stand at a threshold in beginning to make sense of data science and thus big data analytics and data-driven decision-making and the related processes, systems, and methods that will be of massive use and interwoven into the very fabric of smart sustainable cities of the future as complex and dynamic systems within the next decades. We are certainly entering a new era, an increasingly computerized and data-driven urban world where new and more extensive datasources, coupled with advanced data processing technologies, will be of paramount importance to discovering useful and hidden knowledge in large masses of data that no one has been able to discover hitherto for making a wide range of well-informed, strategic, and fact-based decisions across the diverse domains of smart sustainable cities of the future in terms of the underlying operating and organizing processes of urban life. The ultimate aim is to advance different aspects of sustainability by employing more innovative and effective ways to study, assess, enhance, and sustain the contribution of such cities to the goals of sustainable development. Big data analytics, particularly the use and combination of data mining tasks, has tremendous potential to solve complex decision-making problems pertaining to sustainable urban development by better monitoring, understanding, analyzing, and planning smart sustainable cities. Data mining for urban analytics has become a key factor for transforming and advancing the knowledge of smart sustainable cities in terms of sustainability and the integration of its dimensions. Especially, such cities generate huge amount of data which should be harnessed to sustainably enhance their operations, functions, services, designs, and policies. Data mining tasks will help to extract useful knowledge from the available data deluge, which can drive sustainably intelligent decisions with regard to energy transport, traffic, mobility, environment, water and waste management, buildings, land use, design, health care, education, safety, governance, economic development, and the quality of life.

This chapter introduced the data mining and knowledge discovery processes after providing additional context by discussing common types of data mining and knowledge discovery tasks, which allowed us to be more concrete when presenting the overall processes. The various fields (e.g., computer science, information science, complexity science, and formal science) and subfields (e.g., artificial intelligence, machine learning, statistics, pattern recognition, and data visualization) of study related to data science have contributed to the development of a set of canonical data mining and knowledge discovery tasks, namely classification, regression, causal modeling, similarity matching, link prediction, data reduction, clustering, and co-occurrence grouping. These are solved with supervised methods, unsupervised methods, or either. Serving different purposes, each of these tasks has an associated set of solution techniques. An urban analyst or a data scientist specialized in urban analytics typically attacks a new urban sustainability project by breaking it down into parts revealing one or more of these canonical tasks, choosing a solution technique for each, and then devising the solution. One of the aims of carrying out this endeavor expertly, which requires considerable experience and competence, is to ensure an intelligent compromise between what the urban data can predict and output and the objectives of the urban endeavor.

This chapter intended primarily to synthesize, illustrate, and discuss a systematic framework for urban sustainability analytics based on CRISP-DM in response to the emerging wave of city analytics in the context of smart sustainable cities. The proposed data mining framework for urban analytics consists of six components, namely:

1. Urban sustainability problem understanding
2. Data understanding
3. Data preparation

4. Model building
5. Results evaluation
6. Results deployment

The derivation and formulation of this framework is based on CRISP-DM and the outcome of the review. This provides a sort of mapping and justifies the link to and the rationale for the different components of the framework. The prominence of this framework as a set of conceptual tools lies in the value of the related well-defined stages in enhancing the likelihood of successful and relevant results. This framework as a systematic organization is very useful for analyzing a wide variety of urban sustainability problems as part of academic and scientific research endeavors. This framework provides a set of questions that can be asked about a proposed project to help understand whether it is well conceived or is fundamentally flawed with respect to the intended goals in terms of the decision-making pertaining to the fundamental goals of sustainable development. It can be tested and used in empirical applications in the city domain. It has an innovative potential to advance urban analytics by providing a novel way of thinking data-analytically about urban sustainability problems. It will provide fertile insights into how to conduct "big data" studies in the field of urban sustainability. The intent is to enable well-informed or knowledge-driven decision-making and enhanced insights in relation to diverse urban domains with regard to operations, functions, strategies, designs, practices, and policies for increasing the contribution of smart sustainable cities to the goals of sustainable development. This work can serve to bring together city analysts, data scientists, urban planners and scholars, and ICT experts on common ground in their endeavor to transform and advance the knowledge of smart sustainable cities. Indeed, the application of data mining to the systematic study of smart sustainable cities is increasingly attracting scholars and practitioners involved in city endeavors to address a wide range of complex problems pertaining to different dimensions of sustainability. Such an advanced form of urban analytics will open new horizons and provide enormous opportunities for enhancing urban systems and coupling and coordinating urban domains in the context of sustainability.

However, having the best group of urban analysts (data science team) can yield little value in terms of advancing urban sustainability without the appropriate urban data, and conversely, having the right urban data often cannot substantially enhance decision-making and insights without the suitable competency and talent of urban analysts, thereby the complementary role of the two components of the assets in question. Worth noting is that there is, and will be, a shortage of data science competency and talent necessary for smart sustainable cities of the future to take advantage of big data analytics, both urban professionals and scholars with deep analytical skills as well as urban analysts with the know-how to use the analysis of big data to make effective decisions pertaining to urban sustainability. Indeed, as part of the emerging urban analytics approach, it has become of critical importance for urban professionals, researchers, and analyst to understand the fundamental concepts of data science and thus data mining even if they never intend to approach or conceive of sustainability problems data-analytically merely because data analysis is now so critical to urban planning and development strategy. Smart cities and sustainable cities are increasingly driven by big data analytics, so there is a great professional and academic advantage in being able to interact competently (data-analytically) with smart sustainable cities as an emerging urban development approach. Understanding the fundamental concepts of data science, and having and making effective use of this framework for organizing data-analytic thinking, especially the processes of data mining not only will allow urban professionals, researchers, and analysts to interact competently but will help to envision tremendous opportunities for improving different dimensions of urban sustainability based on data-driven decision-making and insights as enhanced outcomes. Cities badging or regenerating themselves as smart sustainable are exploiting new and existing data resources for environmental and socioeconomic gains and benefits. They bring data science teams and urban scholars and practitioners on common ground to bring advanced technologies and practices to bear to increase the contribution of such cities to the goals of sustainable development. Increasingly, urban administrators need to oversee analytics teams and analysis endeavors across the diverse domains of smart sustainable cities, local city governments must be able to invest wisely in urban projects with substantial data assets directed for improving different aspects of sustainability, and urban strategists and policymakers must be able to devise plans and design policies respectively that exploit and leverage data in the needed transition toward sustainability.

Furthermore, big data analytics is changing the paradigm of scientific development, shifting from mainly formulating and testing hypotheses as well as collecting data manually and examining and reflecting on them to relying more and more on data processing, analysis, modeling, simulation, prediction, and verification (Bibri 2018b). This development, which spans many academic and scientific research domains, will help make decisions easier to judge, knowledge-driven, and strategic, and hence support and enhance new practices, strategies, and policies. For instance, big data analytics and related simulation models may completely redefine the problems pertaining to many urban domains and offer entirely innovative opportunities to tackle them, thus doing more than solely enhancing existing practices. Experiences have shown that traditional scientific and academic research paradigms lead to questionable and challengeable assumptions about the evolution of social practices. It may be more beneficial to search for the emergence of new practices around big data analytics and its wider use (in the urban domain). In this sense, new practices can develop around this advanced technology, which can in turn be adapted and integrated into these practices, thereby advancing further its use in a way that fits into a wider strategy or formula that makes this technology more meaningful. In all, big data analytics is becoming increasingly a salient factor for academic and scientific innovation with regard to addressing complex challenges and pressing issues, i.e., responding to major environmental concerns and socioeconomic needs. Indeed, the best opportunity for using big data is to harness and analyze data not as an end in itself—but rather to develop big theories about how smart sustainable cities function and can be managed and planned as to their quest for addressing the challenge of sustainability. In this respect, as part of academic and research endeavors, big data analytics can be exploited to reveal hidden and previously unknown patterns and discover meaningful correlations in large datasets pertaining to natural and social sciences so to develop more effective ways of responding to major paradigm shifts and social trends in the form of new processes, services, designs, and policies. In the meantime, to really get a grip on the use of big data to address the challenge of urban sustainability, new theories are necessary. As West (2013) vividly argues, big data require big theories. As to the functioning of cities, discovering patterns and making correlations in big data can only ever occur through the lens of theory (Batty 2013).

In all, the potential of big data for transforming the knowledge of smart sustainable cities through the creation of a data deluge that seeks to provide novel ways of understanding, managing, and planning complex forms of urbanity stems from the key characteristics of big data (see, e.g., Batty et al. 2012; Bibri and Krogstie 2017c; Boyd and Crawford 2012; Kitchin 2014; Laney 2001; Marz and Warren 2012; Mayer–Schonberger and Cukier 2013; Zikopoulos et al. 2012) in terms of consisting of terabytes or petabytes of data; being created in or near real-time; being structured and unstructured in nature and often temporally and spatially referenced; being exhaustive in scope by striving to capture entire populations or systems, or at least much larger sample sizes than would be employed in small data studies; being fine-grained in resolution by aiming to be as detailed as possible and uniquely indexical in identification; being relational in nature by containing common fields that enable the conjoining of different data sets; and holding the traits of extensionality (can add new fields easily) and scalability (can expand in size rapidly). In other words, big data consists of massive, dynamic, varied, detailed, inter-related, low-cost datasets that can be connected and utilized in diverse ways using advanced techniques, thereby offering the possibility of studies shifting from data-scarce to data-rich that are of high potential for transforming and advancing the knowledge of smart sustainable cities. Also, big data studies enable a shift from coarse aggregation to high resolution; static snapshots to dynamic unfoldings; and relatively simple hypotheses and models to more complex, sophisticated simulations and theories (Kitchin 2013). All in all, scientific knowledge can advance even without coherent models, unified theories, or any mechanistic explanation at all.

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Chapter 5
Unprecedented Innovations in Sustainable Urban Planning: Novel Analytical Solutions and Data-Driven Decision-Making Processes

Abstract City planning is drastically changing with regard to the way urban systems can function and be managed and developed in line with the goals of sustainable development. Marking and fueling this change predominately is the increasing use and application of big data and data-driven decision-making in urban analytics and planning to advance the contribution of cities to sustainability. This unprecedented shift has been instigated by the recent advances in data science and its becoming a more accessible tool to advocacy groups, more extensive data and their new sources being able to potentially allow key stakeholders to see and respond to various urban factors (mobility, transport, energy, environment, public health care, education, etc.) in real time, coupled with citizens emitting rich spatiotemporal data to an increasing extent through the use of various technologies. We refer to big data with respect to their humongous size and wide variety but pay particular attention to urban data, i.e., data invariably tagged with spatial and temporal labels; largely streamed from diverse sensory sources and stored in databases; generated routinely, automatically, and sporadically; and merged and coalesced in data warehouses for use at the citywide scale. This epitomizes a sea change in the data that we generate about urban systems as to what happens and where, when, how, and why in the urban environment. This is opening entirely new windows of opportunity for the application of analytical solutions and data-driven decision-making approaches into urban planning in terms of improving the performance of, and contribution to, the goals of sustainable development under what is termed smart sustainable cities. This chapter explores the real potential of big data and data-driven decision-making for revolutionizing or transforming the process of planning for the purpose of achieving the goals of sustainable development in the context of smart sustainable cities, focusing on different dimensions and functions of planning as well as their synergy and integration. We argue that the increasing proliferation and availability of urban data, coupled with the continuous integration of new and more extensive sources of such data as well as the evolving development of big data technologies, are increasingly enabling novel analytical solutions for, or sophisticated engineering approaches into, advancing the process of sustainable urban development, in addition to seamlessly integrating long-term strategic planning with short-term thinking about how cities can function and be

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managed in the context of sustainability. In addition, we believe that big data innovations entail how new data-driven transformations are facilitated and applied as well as diffused throughout urban systems, rather than simply denoting a significant growth in volume and variety of urban data.

Keywords Smart sustainable cities · Sustainable urban planning
Big data analytics · Data mining · Data-driven decision-making
Urban intelligence functions · Urban simulations models · Mobility data

5.1 Introduction

The rise of ICT (e.g., Hilbert and Lopez 2011; Mayer-Schonberger and Cukier 2013), the spread of urbanization (UN 2015), and the diffusion of sustainability (e.g., Bibri and Krogstie 2017a, b; Höjer and Wangel 2015) are the three most important global trends at play across the world today. They all remain unprecedented in their magnitude and influence in history, and will most likely change the way we live drastically and irreversibly. As these trends will undoubtedly continue to evolve simultaneously, we can reasonably expect that the world will become largely computerized and urbanized within just a few decades, and that ICT as an enabling and constitutive technology will have a key role in winning the battle of sustainability and in addressing the conundrums posed and issues engendered by urbanization. It is therefore an obvious and yet unsurpassed opportunity to use advanced ICT to understand and rise to the challenges of sustainability and urbanization in new ways, and to resolve the many intractable and wicked problems involved in urban management, planning, and development. In fact, there is an increasing recognition that ICT constitutes a promising response to such challenges and problems due to its tremendous untapped potential to catalyze and advance sustainable development (Bibri and Krogstie 2016a). Strengthening the role of digital technologies has actually been, and continues to be, supported by constant endeavors to further unlock the transformational effects of ICT by exploiting and capitalizing on its disruptive and innovative power in relation to urban systems and domains and how these can be integrated and coordinated for increasing sustainability performance in contemporary cities. ICT superiority lies in the novel applications and services that enhance urban performance and the quality of urban life.

Cities have increasingly gained a central role in applying the discourse of sustainable development, as they epitomize the microcosm of the world in terms of encapsulating in miniature its characteristic features pertaining to environmental change, economic development, and social equity. Cities consume 67% of global energy and generate 76% of GHG emissions (Creutzig et al. 2015). In addition to being key generators of environmental pollutants, cities represent key hotspots of vulnerability to climatic hazards and natural disasters resulting from climate change and present complex challenges for social inequality. Therefore, the increasing urbanization implies significant challenges for sustainability (OECD 2012; Bibri and Krogstie 2017a) due to the intensity of economic and social activities and the associated energy consumption and concomitant environmental risks. In other words, the multidimensional effects of unsustainability are set to worsen with urbanization due to the issues it engenders in terms of intensive energy use, endemic congestion, saturated transport networks, air and water pollution, toxic waste disposal, resource depletion, social disparity and vulnerability, public health decrease, and so on (Bibri and Krogstie 2017a). In a nutshell, as a dynamic clustering of people, buildings, infrastructures, and resources (Bibri 2013), urbanization puts an enormous strain on urban systems, thereby stressing urban life in terms of the underlying operating and organizing processes. Urban growth raises a variety of problems that tend to jeopardize the environmental, economic, and social sustainability of cities (e.g., Neirotti et al. 2014).

Many of the existing intractable urbanization and sustainability problems require evidently newfangled ways of urban thinking grounded in a holistic approach and long-term perspective with respect to the planning and development of the built, infrastructural, operational, and functional forms of city systems (Bibri and Krogstie 2017a). In this regard, there is an urgent need to develop, apply, and mainstream innovative solutions and sophisticated methods in the area of urban planning and development. In particular, the way cities can function and be managed and developed with support of advanced ICT has been of utmost importance to strategic sustainable development to achieve the long-term goals of sustainability (Bibri and Krogstie 2017a). To put it differently, the planning of cities as complex systems toward sustainability requires innovative solutions and advanced methods. Besides, cities are seen as main sites of economic, environmental, and social dynamism and innovation contributing to sustainable transformations and thus cultural advancements. Several contrasting roles of cities underscore immense opportunities to utilize their momentum and talents toward more sustainable development pathway. Specifically, they can evolve in ways that address the environmental concerns and meet the socioeconomic needs of their citizens based on innovations, as they are the incubators, generators, and transmitters of creative ideas and smart solutions for solving many challenges (Bibri and Krogstie 2017a). Indeed, a large number of advanced technologies, systems, methods, and techniques pertaining to big data analytics are being developed and applied in response to the urgent need for dealing with the complexity and availability of the knowledge necessary for enhancing, harnessing, and integrating urban systems and facilitating collaboration among urban domains in the realm of smart sustainable urban planning and development (Bibri and Krogstie 2016b). The evolving big data paradigm is increasingly viewed as having significant ramifications in the urban domain (ICSU 2015). The predictive, descriptive, diagnostic analytics, and prescriptive analytics associated with big data innovations have the potential to transform how urbanites interact with each other and their surrounding environment as well as benefit from urban infrastructures and facilities and ecosystem and human services.

As a research direction, big data have recently attracted scholars and scientists from diverse disciplines as well as practitioners from a variety of professional fields due to their prominence in relation to various urban domains, especially urban planning, transportation engineering, sustainable mobility, public health, and socioeconomic forecasting, in addition to being a major intellectual, scientific, and practical challenge (Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Bettencourt 2014). Big data analytics is increasingly seen to provide unsurpassed and innovative ways to address a range of complex environmental challenges and rising socioeconomic concerns facing contemporary cities as to the operational functioning, management, and planning of their systems. Given the emergence of urban big data, urban planners and policy-makers are faced with unique opportunities to develop, experiment, and advance the contribution of cities to the goals of sustainable development. Indeed, there has recently been much enthusiasm about the immense possibilities created by new and more extensive sources of urban data to better operate, manage, and develop cities to improve their contribution to the goals of sustainable development as a result of thinking about and understanding related problems in a data-analytic fashion. Big data are certainly enriching and reshaping human experiences of how cities can be planned. And they are offering many new opportunities for well-informed decision-making and enhanced insights with respect to our knowledge of how fast and best to advance urban sustainability.

The research and practice in the field of smart sustainable cities tends to focus on the identification of the urban domains that are associated with sustainability dimensions (transport, energy, environment, land use, mobility, health care, education, public safety, etc.)—on the basis of big data—for processing, analysis, and modeling so to develop urban intelligence functions and urban simulation models to be employed for strategic decision-making pertaining to sustainable urban planning (Bibri and Krogstie 2017a, b). This also involves how these domains interrelate and can be merged together for enhanced outcomes in terms of sustainable development. The technical features of smart sustainable urban planning involve the application of big data technologies as a set of scientific and technical processes to land use, natural ecosystems, physical structures, spatial organizations, natural resources, infrastructural systems, socioeconomic networks, and citizens' services. Recent evidence (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri and Krogstie 2017a, b) lends itself to the argument that an amalgamation of these strands of urban planning with cutting-edge big data technologies can help create more sustainable and thus livable and attractive cities. In all, the data-driven approach to urban planning is of paramount importance to strategic sustainable urban development. Besides, the functioning, management, and organization of urban systems, processes, and activities in the field of sustainable urban planning require not only complex interdisciplinary knowledge of sustainability, but also sophisticated technologies and powerful computational and data analytics capabilities.

While there is no doubt that large amounts of urban data are being collected and generated on daily basis and in continuous streams across urban systems and domains, there is less clarity on how such data can be used and applied to address the many wicked problems involved in sustainable urban planning. Moreover, despite the recent increase of research on big data in relation to urban planning, the bulk of work has tended to deal largely with, or focus on, smart cities (e.g., Batty 2013a, b; Batty et al. 2012; Bettencourt 2014; Kitchin 2014; Kumar and Prakash 2014). In other words, little attention has been given to the potential and role of big data and data-driven decision-making in transforming sustainable urban planning. There is increasing evidence that significant opportunities are involved and that the contribution of big data analytics to the planning of smart sustainable cities to improve their contribution to the goals of sustainable development is untapped and still inadequately explored (e.g., Bibri and Krogstie 2017a, b). Thus, this is a significant research area that merits further attention. Indeed, the need to shift the focus toward data-driven sustainable urban planning presents a new direction of research in the context of smart sustainable cities (Bibri and Krogstie 2017a, b).

Set against the preceding background, this chapter explores the real potential of big data and data-driven decision-making for transforming the process of planning for the purpose of achieving the goals of sustainable development in the context of smart sustainable cities. The main motivation for this endeavor is to contribute to bringing data-analytic thinking and its enormous advantages to urban planning to advance sustainability.

The remainder of this chapter is organized as follows. In Sect. 5.2, we provide a detailed description of urban planning and highlight its data-driven and sustainability-oriented dimensions. Section 5.3 delves deeper into the next wave of smart sustainable urban planning in light of big data, identifying and discussing a variety of perspectives. In Sect. 5.4, we discuss data-driven decision-making in sustainable urban planning, as well as describe key aspects related to measuring, collecting, and mining urban big data. Section 5.5 addresses urban big data sources and outlines some issues related to the public policy domain of urban big data. In Sect. 5.6, we present a typology of smart sustainable city functions and briefly discuss the need for coordination and coupling. Section 5.7 identifies and briefly discusses the key scientific and evaluative challenges of smart sustainable urban planning. Additionally, it introduces the evaluation methods for smart sustainable cities and points out some limitations and differences, identifies the key evaluative challenges pertaining to existing models of sustainable urban form, and proposes simulation models as an effective way to strategically assess and optimize the contribution of such forms to the goals of sustainable development. In Sect. 5.8, we explain the role and potential of big data in investigating and evaluating the contribution of sustainable urban forms to sustainability. Section 5.9 discusses and illustrates the contribution of the uses of big data to sustainable urban planning and design in terms of tackling the related wicked and intractable problems. In Sect. 5.10, we identify and discuss the opportunities and challenges of urban big data with respect to sustainable development indicators and targets. This chapter ends, in Sect. 5.11, with concluding remarks along with some thoughts and reflections.

5.2 Urban Planning and Its Data-Driven and Sustainability-Oriented Dimensions

Urban planning is a valuable force for achieving the goals of sustainable development. As a management and government function of the city, sustainable urban planning involves formulating a detailed plan to achieve optimum balance of demands for growth with the available resources and the need to protect the environment, or to provide livable and healthy human environments in conjunction with minimal demand on resources and minimal environmental impacts. In more detail, it is the process of guiding and directing the use and development of land, resources, and infrastructures, the protection of the environment, and the distribution and provision of ecosystem and human services—in ways that continuously increase the contribution to the environmental, economic, and social goals of sustainable development. This occurs through ensuring wise management of natural resources, efficient operation and intelligent management of infrastructures and facilities, sustained economic growth, and high quality of life and well-being. The constituent elements and characteristic features of sustainable urban planning involve the built form (buildings, streets, residential and commercial areas, schools, parks, etc.) in terms of monitoring and design, urban infrastructure (transportation, water supply, communication systems, distribution networks, etc.) in terms of operation and control, ecosystem services (energy, raw material, water, air, food, etc.) in terms of provision and distribution, human services (public services, social services, cultural facilities, etc.) in terms of delivery and optimization, and administration (mechanisms for adherence to established regulatory frameworks, governance models, practice dissemination, policy recommendations, technical and assessment studies, etc.) in terms of design, evaluation, and implementation. It is abundantly clear that sustainable urban planning requires making countless and complex decisions about urban forms, designs, operations, functions, strategies, and policies. This requires adopting a holistic approach into decision-making supported by advanced technological systems and methods, thereby the need and relevance for big data technologies and techniques and related data-driven decision-making. To put it differently, new sources of urban data coordinated with urban practice and policy can be applied following fundamental principles of data science and analytical engineering to achieve advanced solutions to urban sustainability problems. Big data analytics for decision-making (basing the decisions on the analysis of big data) can be of use in different areas of urban planning, as we will illustrate and exemplify below. Specific examples of big data uses in urban planning for the purpose of optimization, control, management, evaluation, and improvement in the context of sustainability include, but are not limited to, the following:

- Predicting population growth;
- Predicting energy consumption and GHG emissions;
- Socioeconomic forecasting;

- Grouping, characterizing, and profiling citizens in relation to sustainable lifestyles and behavior;
- Geospatial and temporal analysis;
- Analyzing transport systems and networks for identifying patterns;
- Analyzing travel and commuting behavior for identifying patterns;
- Surveying and analyzing the water and power supply;
- Analyzing public and social services;
- Analyzing the impact and effectiveness of land use;
- Analyzing spatial organizations and urban structures;
- Analyzing policies and their impact and effectiveness;
- Analyzing communication systems and distribution networks performance; and
- Analyzing buildings operational energy on different spatial and temporal scales.

This is part of, as mentioned above, the detailed plan to be formulated for the development and management of urban areas, where consideration is typically given to a wide array of sustainability issues such as air pollution, traffic congestion, land values, zoning codes, legislation and regulation, and social policy. Sustainable urban planning is gaining special importance in, and its prominence is increasing throughout, the twenty-first century, as contemporary cities are increasingly facing issues of urbanization and unsustainability. As a process, it identifies the goals of sustainable development to be achieved, formulates strategies to achieve them, arranges the means and procedures required, and implements, monitors, directs, assesses, and enhances all steps in their proper sequence.

5.3 The Next Wave of Smart Sustainable Urban Planning in Light of Big Data

The evolving smart sustainable urban planning approach has materialized as a result of the recent shifts in smart city approaches and sustainable city models and their ongoing amalgamation driven by their efforts for increasing their contribution to the goals of sustainable development. There has been a shift from digital city, intelligent city, networked city, knowledge city, information city, and so on to smart cities, and currently, there is an ongoing shift from smart cities to smarter cities, namely ubiquitous cities, sentient cities, ambient cities, and cities as Internet-of-everything (Bibri and Krogstie 2017a). Another evolving shift is from smart cities to more hybrid forms of cities, such as eco-knowledge city, real-time sustainable city, sustainable ubiquitous city, and so on, which all constitute early instances of smart sustainable cities. Similarly, the application of sustainable development to the planning and design of cities has resulted in the emergence of several sustainable urban forms, most notably compact city, eco-city, green urbanism, and new urbanism. Worth noting in the event of these shifts is that urban ICT as applications of scientific innovations in urban computing has been evolving just as the underlying social knowledge of how to understand ICT systems (e.g., big data technologies) and the way in which they can be applied (e.g., the use of data mining and statistics in urban analytics) to transform cities in better ways are evolving. This is predicated on the assumption that science-based technologies develop dependently of cities as a microcosm of society, in a mutual shaping process where they both are shaped at the same time and thus affect one another and evolve. In a nutshell, science and technology shape and influence cities as social fabrics and vice versa. The underlying premise is that big data as a set of technological systems and applications in the form of scientific knowledge are embedded in the urban context as part of the wider social context within which they arise (Bibri and Krogstie 2016a). The social and thus urban conditions as structures and processes affect scientific knowledge and activity in relation to data science and big data technologies, which in turn shape urban analytics and planning, to draw on Joseph and Sullivan (1975). Social studies of science demonstrate that scientific knowledge and related system of production are shaped by the wider social context in which scientific inquiries and endeavors take place (Latour 1987; Latour and Woolgar 1986). Accordingly, as reported by Bibri and Krogstie (2016a, p. 1), smart sustainable cities and what they entail in terms of data-driven urban analytics and planning approach “are mediated by and situated within ecologically and technologically advanced societies. As urban manifestations of scientific knowledge and technological innovation, they are shaped by, and also shape, socio-cultural and politico-institutional structures,” especially those pertaining to the urban sphere of society. In all, the conception of smart sustainable cities epitomizes a product of a shift from seeing the city as a stable or constant structure to seeing it as an informational landscape which orchestrates and coordinates the various computational entities in the physical space into an open system. It follows that the sustainable urban planning approach is in light of data science shifting from focusing on physical and spatial development toward relying more and more on big data analytics and related intelligence functions and simulation models for decision-making as a way of applying sustainability principles. This crystallizes the idea that the traditional urban planning model can no longer handle current planning conceptions and address emerging challenges in an increasingly technologized, computerized, and urbanized world. In other words, as such model is “predicated on the basis that the city is a stable unchanging structure” (Batty et al. 2012), it is no longer suited for handling the hitherto ungraspable complexity associated with the very use of technologies to understand cities as complex systems. As supported by Batty et al. (2012), the urban planning systems currently in use “are not fit-for-purpose,” and hence the shifts that need to be instigated are the kind of unprecedented paradigm changes. This entails in the context of smart sustainable cities the development, deployment, and coordination of ICT infrastructures, applications, and services and the underlying distributed and heterogeneous environments in terms of sensing, data processing, cloud computing, and wireless networking on the citywide scale for a wide connectivity, accessibility, and use for all urban entities, as well as for collective intelligence functions and service delivery systems (Bibri and Krogstie 2017a). Adding to this is the use of advanced big data analytics techniques capable of handling billions of observations, transactions, and interactions for discovering new knowledge necessary for managing and developing cities and redesigning existing ones. All in all, the way in which cities are understood and conceptualized is changing: from being viewed as closed and static systems to being seen as complex, dynamic, adaptive, and evolving systems in terms of their behavioral patterns and internal and external interactions. In this regard, many scholars in different disciplines (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Batty 2013a; Bibri and Krogstie 2017a, b; Kitchin 2014; Khan et al. 2015; Shahrokni et al. 2015) advocate the inclusion of ubiquitous sensing, data processing, and wireless networking technologies into urban planning as a core feature of smart sustainable cities of the future. This is marking the next wave of sustainable urban planning and what it entails as to design, evaluation, organization, and forecasting of physical arrangements and urban infrastructures and the associated processes, activities, and services.

One of the salient driving factors for urban planning embracing the wave of data-driven smartness lies in the fertile environment and immense opportunity being created through the utilization of the innovative solutions and sophisticated methods increasingly enabled by big data technologies for storage, processing, and management that are designed and applied for supporting the goals of sustainable development. This is manifested in the rapid evolvement of smart sustainable cities as a new urban development approach into becoming more and more data-analytically driven in thinking and planning as to sustainability issues. In several information societies, national urban development projects are investing heavily in, and focusing on strengthening the role of, big data analytics in sustainable urban planning and development. If a sustainable urban development strategy is understood as what smart cities are doing to incorporate the goals of sustainable development and sustainable cities are doing to smarten their contribution to these goals and how they do it, then the scholarly enterprise of big data and its increasing role in catalyzing and boosting the process of sustainable urban development and thus in facilitating the contribution of both smart and sustainable cities to its goals is most likely to represent an important changing dynamic in the transition to smart sustainable cities based on data-driven analytics and planning practices. In a nutshell, smart planning is of paramount significance to strategic sustainable urban development (Bibri and Krogstie 2016a, 2017a). The underlying premise is that the operation, management, arrangement, organization, assessment, and design of urban systems in the field of sustainable urban planning increasingly require sophisticated technologies and profound data analytics capabilities to leverage the related complex interdisciplinary knowledge. Currently, smart urban development strategies are about harnessing ideas about how big data technologies can improve operational functioning, optimize efficiency, enhance the quality of life, and, more importantly, help devise new approaches into tackling environmental and socioeconomic problems on the basis of the automated extraction of useful knowledge from large masses of data for well-informed, strategic decision-making in the realm of smart sustainable cities. The value of big data in the urban context lies in finding more effective and innovative ways of how data can be applied and how new data-driven innovations can be facilitated and diffused throughout the domains of smart sustainable cities for instigating and stimulating the sought-after transformations. One key facet of such transformations is how to improve the different dimensions of sustainability by translating it into the built, spatial, infrastructural, operational, functional, and serviceable forms of cities. Besides, the traditional sustainable urban planning approach alone is no longer of pertinence in terms of ensuring the effectiveness of the operation, management, organization, assessment, and design of urban systems in terms of addressing the challenge of sustainability. In relation to this, Neuman (2005) contends that conceiving cities in terms of forms remains inadequate to achieve the goals ascribed to sustainable cities; or rather, accounting only for urban form strategies to make cities more sustainable is counterproductive. Instead, conceiving cities in terms of "processual outcomes of urbanization" holds great potential for attaining the goals of sustainable development, as this involves asking the right question of "whether the processes of building cities and the processes of living, consuming, and producing in cities are sustainable," which raises the level of, and may even change, the game (Neuman 2005). In this respect, Townsend (2013) portrays urban growth and ICT development as a form of symbiosis. This entails a mutually beneficial relationship between ICT and urbanization (Bibri and Krogstie 2017a). This process-driven perspective paves the way for a dynamic conception of urban planning that reverses the focus on urban forms governed by static planning tools; this holds more promise in attaining the elusive goal of urban sustainability (Neuman 2005). Innovative ICT as a strategy "integrates technologies, systems, infrastructures, services, and capabilities into an organic network that is sufficiently complex for unexpected emergent properties to develop" (Nam and Pardo 2011, p. 288). In the spirit of calling for joined-up urban planning, the idea of data magnitude and scope, coupled with the use of advanced big data technologies in the processes operating and organizing urban life at the micro- and macro-levels is that the extraction of useful knowledge from large masses of data using powerful analytics techniques can improve urban performance on multiple scales and handle different levels of complexity through a variety of deployed solutions. A joined-up planning refers to a form of an across-the-board "integration that enables system–wide effects to be tracked, understood, and built into the very responses and designs that characterize the operations and functions of the city. This relates very strongly to the…theme involving connection, networks, and data integration" (Batty et al. 2012, p. 491). This is at the core of the systemic and holistic approach that underlies urban sustainability in terms of the embeddedness of collective intelligence functions into the fabric of the existing institutions and organizations of smart sustainable cities whose mandate is ensuring and producing a high quality of life and well-being for their citizenry through pursuing the path of sustainable development. In all, further advances in big data technologies will most likely reshape how to address and overcome, as part of urban planning and development, the challenge of sustainability involving diverse urban domains in ways that were, in many cases, not even conceivable, even two decades ago.

Data science is increasingly pervading many city-related disciplines and thus urban planning subfields, especially environmental planning, transportation planning, land-use planning, energy planning, sustainable development, urban design, and research and analysis, where big data technologies and innovations are considered key to the building and implementation of diverse models generated through predictive, descriptive, diagnostic, and prescriptive analytics; the advancement of database design and integration; the improvement of data processing platforms and cloud computing infrastructures; and to the diffusion of wireless networks—smart sustainable cities' basic infrastructure backbone. Smart sustainable cities as complex systems can only be studied or investigated in an interdisciplinary context, and related structures, forms, and evolutionary development should be treated as complex subsystems that are to be handled by data science as an interdisciplinary field about scientific systems, processes, and methods. Such cities are too complex to deal with without using big data technologies and innovations to monitor, understand, probe, and plan them to improve and sustain their contribution to the goals of sustainable development. Hence, urbanity, the way of life characteristic of cities, has become as much a function of sensed, processed, analyzed, modeled, and simulated urban data as part of distributed urban computing as it is of an organized, coordinated, and standardized physical arrangement and infrastructural system and the underlying processes and activities (e.g., Batty et al. 2012; Batty 2013a, b; Bibri and Krogstie 2017a, b; Böhlen and Frei 2009). This implies that sustainable urban planning requires not only complex interdisciplinary knowledge but also sophisticated technologies and thus profound data computation and analytics. Accordingly, smart sustainable urban planning involves the application of advanced ICT as a set of scientific and technical processes, techniques, and methods (based on data science, computer science, information science, and complexity sciences) to land-use patterns, natural ecosystems, physical structures, spatial organizations, natural resources, infrastructural systems, socioeconomic networks, and citizens' services (Bibri and Krogstie 2017a).

The development of smart sustainable cities entails thinking about and conceiving of the urban environment as constellations of instruments across spatial and temporal scales that are networked in multiple ways to provide continuous data coming from various systems and domains, in order to monitor, understand, and analyze how cities function and can be managed and planned in ways that guide and direct their development toward sustainability. Big data analytics provides fascinating opportunities to change how things can be done and handled in such cities on several scales. Consequently, smart cities are getting smarter as to incorporating the goals of sustainable development (e.g., Batty et al. 2012) and sustainable cities as to smartening up their contribution to sustainability thanks to the opportunities and capabilities being offered by big data technologies (e.g., Bibri and Krogstie 2017b). The existing evidence (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Creutzig et al. 2015; ICSU 2015) lends itself to the argument that an amalgamation of such strands as urban design, land use, natural ecosystems, physical structures, spatial organizations, natural resources, infrastructural systems, socioeconomic networks, and ecosystem and human services with big data ecosystems in relation to urban planning and development will help to create more sustainable cities in terms of livability, safety, efficiency, and resilience.

5.4 Data-Driven Decision-Making and Related Processes in Sustainable Urban Planning

The data-driven approach into urban planning is heralding major changes in understanding and conceiving of sustainability and tackling related challenges and problems under what is termed smart sustainable cities as a techno-urban vision yet to be realized. Smart sustainable cities entail many domains associated with the different dimensions of sustainability, including transport, mobility, land use, energy, environment, health care, education, governance, public safety, and so on, as well as how these domains interrelate and can be merged together for enhanced outcomes. The related data can be collected, coalesced, processed, analyzed, and modeled so to develop urban intelligence functions and urban simulation models to be employed for strategic decision-making pertaining to urban planning that supports the goals of sustainable development (Batty et al. 2012; Bibri and Krogstie 2017a, b). The massive repositories of all kind of urban data represent a sea change in the data that we generate about urban systems as to what happens and where, when, how, and why in the urban environment, which provides great opportunities to apply analytical solutions and data-driven decision-making approaches into sustainable urban planning. In fact, big data analytics is drastically altering the way both smart cities and sustainable cities can be planned and developed across multiple spatial and time scales (Batty 2013a; Batty et al. 2012; Bibri and Krogstie 2017b). This offers the prospect that cities can be made smarter and more sustainable in the long term thanks to the potential of reflecting over the short term in a continuous manner. Big data are increasingly pushing the city planning into short termism (Batty 2013a), which is adding a new dimension to the process of sustainable development. In more detail, one of the key uses of big data is enabling and supporting short-term thinking about and planning of how emerging smart sustainable cities can function and be managed, thereby shifting the emphasis away from long-term strategic planning—what takes place in cities measured, evaluated, modeled, and simulated over years or decades. This has prevailed in urban studies and planning theories for more than half a century. As stated by Batty (2013a, p. 276), urban big data can be employed "to derive rather new theories of how cities function in ways that focus on much shorter term issues than hitherto, and much more on movement and mobility than on…the long-term functioning of the city system. This is city planning in a new guise—that is, thinking of cities as being plannable in some sense [more routinely] over minutes, hours and days, rather than years, decades or generations." Indeed, in relation to data-driven urban analytics, the urban analysts are often expected to produce answers in days rather than months (where analytical solutions often are only a piece of the larger solution to the urban problem being tackled), work by exploratory analysis and rapid iteration based on processes with well-defined stages, and to produce and present results with dashboards by displaying them in an understandable format for human interpretation rather than reports (see Chap. 4 for a detailed discussion). This entails using data and analytical talent to find and interpret rich data sources, managing large volumes of data while dealing with several technical constraints, integrating data sources, ensuring consistency of datasets prior to processing, building diverse models based on patterns from data, creating visualizations to aid in understanding data, and presenting and communicating the results and insights. In relation to sustainable urban planning, the deployment of results of big data analytics techniques (data mining, statistics, database query, etc.) can be technical (e.g., procedures related to energy or traffic management systems), less technical (e.g., a set of rules discovered by data mining to help to quickly diagnose and fix a common error in service delivery), and much more subtle (e.g., a change to strategies, practices, and policies resulting from enhanced insight gained from mining the urban data).

Furthermore, the goal of data science in this context is to enhance strategic decision-making in the planning of the diverse domains of smart sustainable cities through the practice of basing decisions of planning on the analysis of data—data-driven decision-making. This relates to the process of directing and guiding the development of smart sustainable cities toward achieving the long-term goals of sustainability. Thus, the way the systems of such cities as operating and organizing processes of urban life can be monitored, understood, analyzed, managed, and planned to respond to the challenge of sustainability is drastically changing thanks to big data analytics and its potential to enable powerful intelligence functions and simulation models for decision-making. This unprecedented data-driven change in urban management and planning has been made possible by data science and what it entails in terms of scientific systems, processes, and methods used to extract useful knowledge from large masses of urban data. The processes of data mining and knowledge discovery are by far seen as the most widely used approaches into extracting useful knowledge from data for enhanced decision-making and insights pertaining to planning in terms of evaluation, forecasting, design, and so on in relation to various domains in the context of smart sustainable cities. Accordingly, the knowledge resulting from the processes of data mining and knowledge discovery can be used for supporting different kinds of decisions associated with urban planning. The sort of decisions we are concerned with are the ones for which meaningful discoveries need to be made within urban data, which could be found through formulating urban sustainability problems and devising relevant solutions to them data-analytically. Such decisions are associated with optimization, control, management, improvement, and assessment relating to urban operations, functions, services, strategies, practices, and policies in the context of smart sustainable cities with regard to their contribution to the goals of sustainable development. Several environmental, social, and economic indicators could be extracted from urban data; assembled into predictive or descriptive models related to mobility, travel, traffic, energy, environment, health care, education, and so on; and then deployed in the processes operating and organizing urban life as part of data-centric applications facilitating planning across a variety of urban domains. In all, as the clearest illustrations of data science principles, the processes of data mining and knowledge discovery are drastically changing urban analytics, which in turn reshaping urban planning as to a variety of its areas, including land-use planning, transport planning, environmental planning, domain coordination, strategic thinking, policy recommendations, administration, and urban design in the context of sustainability.

In the context of smart sustainable cities, many different initiatives in collecting data from new varieties of digital access are being fashioned, such as the satellite-enabled Global Positioning System (GPS) in vehicles and on citizens, from social media sites, from transactions, and from access to numerous kinds of web sites. Satellite remote-sensing data are also becoming widely deployed, in addition to a variety of scanning technologies associated with the IoT as a form of UbiComp. Within the next decade, most of the data that can be used to monitor, understand, analyze, and plan smart sustainable cities will come from digital sensors recording observations, movements, interactions, and transactions, and will be available in various forms, with temporal tags as well as geotags in many instances. This will pave the way for big data to become the dominant mode of urban analytics in relation to different urban planning functions, which requires to exploit and extend a variety of data mining techniques through which the visualization of patterns and correlations in the form of a variety of advanced models will be of utmost importance in terms of their use for advancing the contribution of smart sustainable cities to the goals of sustainable development. These tools and methods will be utilized based on the needs of urban planning in the form of formulating and solving different urban sustainability problems using data mining solutions (see Chap. 4 for more details). The urban big data are evolving, the related movement is gaining momentum, and the use of big data technologies is sharply focussed on how we might integrate data using novel forms of data warehousing as well as powerful forms of database design and integration adapted to and distributed at the city-wide scale. As part of urban big data, open and crowdsourcing data are key to many new datasets that will be useful to smart sustainable cities with respect to what we think about key sustainability problems. Another fundamental element of the new wave of urban analytics that is emerging is big datasets pertaining to human mobility, fostered by the widespread diffusion of wireless and mobile technologies for capturing GPS tracks from navigation devices and for recording call details on mobile networks as well as daily movements of citizens. Thus, these network infrastructures allow for sensing and collecting massive repositories of spatiotemporal data, which provide a powerful social microscope and represent society-wide proxies for human mobile activities (Batty et al. 2012). These big mobility data may help us understand human mobility in relation to different principles of sustainable urban planning and design, in addition to discovering the hidden patterns and correlations based on descriptive modeling, which provides characteristic information about the trajectories people follow during their daily movements and activities. Large-scale experiments will enable to find solutions to many urban sustainability problems entailing challenging analytical questions about mobility behavior and involving a wide variety of data mining techniques (classification, clustering, regression, profiling, link prediction, etc.). There are numerous urban (environmental, economic, and social) sustainability questions that the urban analysts need to disentangle. And finding answers to these questions is still beyond the processing capabilities of the current generation of big data analytics techniques, but these limits will be pushed back with new advances in the field of data science, coupled with the prospect ICT of the new wave of computing offers as to providing dramatically new and rich datasets that will inform many sustainability problems along with technically matured pervasive computing environments.

Concerning the pervasive sensing of complex social systems using the ubiquity of mobile phones, the concept of reality mining (Eagle and Peatland 2006) is a key determinant of how citizens interacting with each other in smart sustainable cities of the future can become smarter and more sustainable. The analysis of datasets derived from reality mining, which entails logging location, communication activity, and service and application usage, helps to extract eigenbehaviors to identify structure in everyday activities (Eagle and Peatland 2009). This holds huge potential to gain new insights into urban dynamic processes at high spatiotemporal resolution at the city scale, and the key areas of interest include mobility and accessibility patterns, data-driven characterization of urban operational functioning, spatial characteristic features in social network structure, and collective behavior identification, all based on richly descriptive data mining models (Batty et al. 2012). To fully realize the idea of an urban mobility atlas (a comprehensive catalogue of the mobility behavior) for smart sustainable cities of the future, which can be developed from data mining and network analysis, it is necessary to use advanced forms of database integration to be able to merge richer sources of mobility data, including the data from road sensors, public transportation, surveys and official statistics, and participatory sensing, into coherent databases, as well as to link mobility to socioeconomic networks, which will be extremely relevant to understanding how public energy saving transportation systems could meet the demand for individual mobility (see Batty et al. 2012), among other things related to urban sustainability. In this context, an atlas can be browsed based on a set of criteria, including geographic area, the hours of the day, and the days of the week so to explore the rhythmical throbbing of smart sustainable cities in varying circumstances and concurrently monitor and observe potential deviations from normal behavioral patterns, to draw on Batty (2010).

5.5 Urban Big Data Sources

The systems and domains of smart sustainable cities should function and be managed and developed using advanced data, information, and communication technologies. This entails an effective integration of urban planning and design principles and technological innovations and capabilities in order to be able to better monitor, understand, analyze, and plan such cities to improve their contribution to the goals of sustainable development. Urban systems and domains constitute the main source of urban data, which are generated by various urban entities, including city government, city authorities, urban departments, urban administrators, academic institutions, enterprises, communities, and individual citizens. They provide heterogeneous and colossal amounts of data, which are generated in continuous streams and on daily basis from sectoral and cross-sectoral sources. Examples of urban data include observational data, transactional data, environmental data, economic data, geospatial data, temporal data, administrative records, call detail records, household-level surveys, individual and collective mobility records, travel and transportation data, citizenry science, surveys and official statistics, social media and participatory sensing, social network surveys, and so on. In other words, in the urban environment, urbanites, processes, systems, structures, activities, networks, facilities, services, and objects all contribute to producing large masses of data involving heterogeneous and distributed sources, including but not limited to the following:

- Land use;
- Spatial organizations;
- Physical structures;
- Socioeconomic networks;
- Life quality and well-being indicators;
- Transport and traffic systems and networks;
- Energy and environmental systems;
- Commuting behavior of citizens and movements of goods;
- Water and energy distribution networks;
- Natural ecosystems and resources;
- Public and social services;
- Economic development;
- Participatory sensing and social media;
- Education, culture, and healthcare facilities; and
- Governance and citizen participation.

Urban big data are to be captured, collected, stored, and integrated for later processing, analysis, visualization, deployment, and sharing throughout the informational landscape of smart sustainable cities in order to support decision-making related to urban operations, functions, designs, services, practices, and policies. Set to grow exponentially, such data can be viewed as the most scalable and synergic asset of smart sustainable cities in terms of their employment to drive decision-making associated with urban management and planning. This is an effective way to open new windows of opportunity for such cities to utilize their momentum and talent toward more sustainable development pathways. Yet, the opportunity driven by big data in urban planning needs to be fully understood and exploited, while big data technologies should be continuously improved and effectively applied for achieving the desired outcomes in terms of sustainability. Currently, the potential of big data and data-driven decision-making as innovations lies in transforming urban planning in ways that formalize and systemize its approaches into advancing the contribution of both smart cities and sustainable cities to the goals of sustainable development to evolve into smart sustainable cities of the future. This transformation involves innovative ways of not only management and planning, but also monitoring, understanding, and analyzing the systems and domains of both of these classes of cities toward achieving the required level of sustainability.

However, it is critically important to provide guidelines and principles to facilitate the integration of all the different cross-thematic data categories into coherent databases prior to any kind of analysis (data mining, statistics, regression analysis, machine learning, database query, etc.). The underlying assumption is that urban big data are generated from widely different and at times unstructured sources, each with particular format and related methodological and technical challenges. In this regard, research on urban big data should focus on addressing several issues related to the public policy domain of urban big data, including the following:

- How to collect and coalesce various types of large data in city data warehouse;
- Which urban entities (stakeholders) should be involved within different urban domains;
- What concerns are of relevance for the diffusion of big data technologies and platforms;
- The interoperability between various data standards (open, proprietary, etc.);
- How urban citizens should be involved in the decision-making process pertaining to the selection and deployment of urban big data innovations; and
- The ethical and legal dimensions in terms of data access and control and thus privacy and security.

To provide a very rich nexus of possibilities in terms of providing new and open sources of urban big data necessary for better understanding smart sustainable cities and how they function and can be managed and developed requires collecting, meshing, and analyzing various types of data (observational, transactional, mobile, etc.) with the automation of standard secondary sources of data and unconventional data elicited from participatory sensing and social media, using and combining a wide variety of satellite remote-sensing, GPS and other sensors, online interactive data systems associated with crowdsourcing, scanning technologies, and so forth.

5.6 The Need for Coordination and Coupling: A Typology of Smart Sustainable City Functions

Coordination, coupling, and integration are different perspectives in planning and developing smart sustainable cities, which can be viewed as programs of connecting up their systems in terms of operations, processes, and services for more effective functioning. This requires advanced forms of database integration, new software platforms for linking hitherto unconnected domains in urban functioning; an entirely new holistic system that integrates data collection, mining/discovery, and querying; and new forms of institutional setups and governance arrangements, which can enable this interconnection of platforms, systems, and applications to become effective and diffused. Important to note is that such connectivity should be done for the purpose of achieving the goals of sustainable development as identified in the first step of the process of sustainable urban planning. In particular, integrating databases from across diverse urban domains as well as the underlying components with respect to operations, processes, and services based on networking coordination typify powerful intelligence functionalities for enhancing sustainable development processes. Smart sustainable cities balance efficiency and life quality against the environment and equity through advanced ICT with a focus on improving the ability of their citizenry to innovate and contribute through active participation, cooperation, and engagement. For example, in relation to the development of technologies that ensure equity and realize a better quality of life, efficiency must be balanced with equity as emerging technologies have a propensity to polarize at many levels and thus open up different divides, and there is a need to explore how new forms of regulation at the level of urban planning and community development can be enhanced using future technologies (see Batty et al. 2012). The goals of sustainable development lie behind the mission statements produced by city governments for smart sustainable cities. Here, we show an exemplar of how various domains might connect up with reference to smart sustainable cities of the future (Table 5.1).

5.7 Key Scientific and Evaluative Challenges of Smart Sustainable Urban Planning

Smart sustainable urban planning inherits the majority of the scientific challenges associated with smart city approaches and the evaluative challenges pertaining to sustainable city models. It is required to address and overcome these challenges in order to adhere to the vision of sustainability in an increasingly technologized, computerized, and urbanized world.

5.7.1 Scientific Challenges

The major scientific challenges of the planning and development of smart sustainable cities encompass the following:

- To relate smart sustainable cities in terms of their typologies, infrastructures, ecosystem services, human services, and governance models to their operational functioning, planning, and development through monitoring, analysis, evaluation, modeling, simulation, prediction, and intelligent decision support based on big data analytics and context-aware computing as a set of advanced technologies and novel applications for optimization, control, automation, management, strategy development, and policy design in the context of sustainability. In this respect, the efforts should be directed toward demonstrating how developments in big data analytics and context-aware computing

Table 5.1 A typology of smart sustainable city functions

Smart sustainable built environment	Smart sustainable citizens	Smart sustainable governance
• Data-driven density • Data-driven mixed land use • Data-driven diversity • Data-driven sustainable transportation • Data-driven integration of design concepts and typologies	• Cultural enhancement • Lifelong learning and creativity • Social and ethnic plurality/diversity • Sustainable and greener lifestyles • Tolerance and open-mindedness • Active involvement in public life	• Equity and fairness • Involvement in decision-making • Transparent and collective governance • Democratic processes • Public participation • Public and social services
Smart sustainable mobility	Smart sustainable environment	Smart sustainable living
• Spatial and nonspatial accessibility • Virtual mobility • Balanced mobility and accessibility • Car and bicycle sharing • Innovative and safe transport systems • Walking and cycling • Proximity of services and facilities • Diversity of commuting modes	• Green infrastructure • Attractive urban places and images • Open landscapes • Air quality and environment protection • Ecological diversity of urban places • Sustainable and intelligent resource management	• Social cohesion and inclusion • Cultural facilities • Education facilities • Public safety and civic security • Housing quality • Public utility (water, electricity, etc.) • Health conditions • Job opportunities
Smart sustainable planning	Smart sustainable economy	Smart sustainable energy
• Data-driven environmental planning • Data-driven sustainable development • Data-driven transportation planning • Data-driven land-use planning • Data-driven economic forecasting • Data-driven policy recommendations • Data-driven strategic thinking • Data-driven research and analysis • Data-driven administration	• Green entrepreneurship • Integration of environmental concerns into economic decision-making • Data-driven business processes • Optimum balance of technological and human resources in labor market • Optimal utilization of resources • Green investments • Green ICT for economic innovation	• Integrated renewable solutions • Clean/green technology • Data-driven grid management • Context-aware buildings operation • Dematerialization and demobilization • Context-aware appliances operation • Data-driven transport systems • Data-driven urban efficiency • Context-aware energy supply

and the underlying core enabling technologies (namely sensor networks, data processing platforms, middleware architectures, cloud computing infrastructures, and wireless networks) can be integrated so to make smart sustainable cities intelligently more sustainable in the way urban planners, administrators, departments, and authorities can use new technological applications, services, and capabilities for improving sustainability and integrating its dimensions.

- To explore the idea of smart sustainable cities as techno-urban innovation labs, which entails developing intelligence functions as new notions of operational functioning, management, and planning. These intelligence functions can—based on the use of data science, computer science, and complexity sciences in developing advanced simulation models and optimization methods—allow for monitoring and planning smart sustainable cities with respect to the efficiency of energy systems, the improvement of transport and communication systems, the effectiveness of distribution systems, the optimal use and accessibility of facilities, the efficiency of public and social service delivery, and the optimization of ecosystem service provision.
- To construct and aggregate several urban simulation models of different situations of urban life pertaining to the way existing urban systems can be integrated and different urban domains can be coordinated, as well as to how human mobility data can be linked to spatial organizations, transport systems and networks, travel and commuting behavior, socioeconomic network performance, environmental performance, and land use. This should be done in connection with the vision of sustainability as a holistic approach (see Chap. 6 for a detailed discussion). Adding to this is to explore and diversify the approach to the construction and evolution of simulation models. This is to inform the future design of smart sustainable cities on the basis of predictive insights and forecasting capabilities. This is becoming increasingly achievable due to the recent advances in, and pervasiveness of, sensor technologies and their ability to provide information about medium- and long-term changes in the realm of real-time cities.
- To improve different aspects of physical and virtual mobility using ICT of various forms of pervasive computing in terms of combining big data analytics and context-aware computing, in particular in relation to such typologies as density, diversity, compactness, and mixed land use, supported by sustainable and efficient transport systems as well as advanced communication applications. Thereby, both spatial and nonspatial accessibilities can be enhanced in terms of job and social opportunities as well as city services and facilities, thus enabling the citizenry to increase their levels of well-being and life quality.

5.7.2 On the Evaluation of Smart Sustainable Cities

Smart sustainable cities as urban development projects are highly complex and multidimensional—as they deal with wicked problems. Hence, when evaluating them, it is necessary to espouse methods that enable to handle their underlying complexities and to capture their diverse values and multiple purposes. Especially, evaluation methods provide unique windows of opportunity for understanding the outcomes and gauging the impacts of the implemented projects and programs of smart sustainable cities, and for learning from experiences in ways that allow urban planners to improve future sustainable urban development endeavors.

5.7.2.1 Evaluation Methods with Inherent Limitations

As one of the standards evaluation methods, formative evaluation is inadequate to assess smart sustainable cities as urban development projects, if the key purpose is to learn about such endeavors which are characterized by long planning horizons and complex implementation strategies. This is because formative evaluation is intended to support the process of improving ongoing urban projects, and thus involves solely the instrumental use of results, which occurs when actions follow from the evaluation (Patton 1996). This relates to the rational perspective of evaluation, which entails reviewing the implementation of urban projects designed to achieve a set of objectives for solving problems (Stame 2004) as they evolve. Still, while formative evaluation contributes substantially to new urban development projects, it is hardly ever the sole basis for subsequent improvements (Patton 1996). In all, formative and other traditional evaluations remain limited merely because they fail to capture all the purposes of the evaluation of urban development projects. As Patton (1996) argues, formative evaluation is not sufficiently all-inclusive to cover the entire, diverse, and evolving field of evaluation practice which has become too rich and varied to be pigeon-holed into a single approach. Stame (2004) points out that the major shortcoming of traditional evaluation methods is the role of the evaluator as a methodological specialist rather than a social scientist (or expert in socio-technical transitions) with relevant theoretical expertise. In other words, additional dimensions are needed beyond gauging the impact of urban development projects or programs, e.g., whether they were successful or not based on overall evaluative conclusions. There is a wide variety of evaluation methods that can provide such dimensions, such as theory-based evaluation (TBE), stakeholder model evaluation, participatory evaluation, knowledge-generating evaluation, developmental evaluation, and so on.

5.7.2.2 Evaluation Methods Beyond Learning About Sustainable Urban Development Programs

Most sustainable urban development programs are based on a series of premises rather than on some modicum of theories about how to achieve urban sustainability goals, thus the relevance and importance of TBE. This approach provides new dimensions by yielding beyond the findings of standard or formative evaluation and helps to explicate how and why sustainable urban development projects realize the results or fail to achieve them (Patton 1996). This is due to the fact that it requires surfacing the assumptions on which such projects are based in considerable detail: what activities are conducted, what effect each particular activity has, what the expected response is, and what happens next to these expected outcomes, in addition to the evaluation following each step in the sequence (tracking each link in the chains of assumptions) to see whether the expected mini-steps actually materialized (Brickmay and Weiss 2000). TBE has therefore many benefits in terms of supporting and learning about sustainable development in the context of smart sustainable cities, including program planning and improvement (e.g., identifying inadequate or unnecessary program components); the planning and conduct of the evaluation of the specific urban development project (e.g., finding intermediary changes, raising questions, and contributing to paradigm shifts); and the growth of knowledge about human behavior and behavior change (e.g., the difficulties of going to scale and providing clarity and focus for evaluation) (Brickmay and Weiss 2000). Therefore, TBE is an effective way to understand the impacts of sustainable urban development projects and learn how to improve them as part of future endeavors. Stame (2004) contends that what goes into a given project does not necessarily explain the results of that project. Hence, there is a need for a theoretical explanation for the cause and effect of every step or action taken during the evaluation process. TBE “follows each step in the sequence to see whether the expected mini-steps actually materialized” (Stame 2004, p. 408), to reiterate. It is of importance to test the theories developed during the planning process of sustainable urban development programs or projects and hence collect data at many points along the course of such programs or projects. It is though important to keep in mind that theories are not expected to be completely right, to make best use of the information provided by TBE, and to consider theory development as a stage in the evaluation (Stame 2004).

Stakeholder-based model of evaluation is also useful. This approach emphasizes the active involvement of a wide variety of stakeholders in different phases of the evaluation process, as well as ensures that they are given the opportunity to take part in generating the results of this process. Johansson and Lindhult (2008) point out that evaluators as researchers take an active role in assisting stakeholders, which is an important constellation for sustainable urban development. This role is contingent on the type of stakeholders being involved and issues being addressed. Researchers guide open, discursive, and democratic dialog among the involved stakeholders such that they can reach consensus and gain substantive knowledge based on shared experiences (Johansson and Lindhult (2008). Drawing on Cousins and Earl (1992), stakeholder model attempts to engage a large number of potentially interested members of the urban project to create support and involve these members in a consultative way to clarify domains and establish the evaluation questions; also, in this model, the evaluator, the principal investigator, translates the institutional requirements into a study and carries it out.

As far as concerns participatory evaluation, this approach provides several benefits. Entailing a partnership between trained evaluation personnel and practice-based decision-makers, city organization members with project responsibility and primary citizens, participatory evaluation engages a relatively small number of primary citizens in the "nuts and bolts" of the problem formulation, instrument design, data collection, analysis, recommendations, and reports; and in this approach, the evaluator is the coordinator of the urban project with responsibility for technical support, training, and quality control; moreover, conducting the study remains a joint task and practitioners "learn on the job" under the close supervision of the expert evaluator, to draw on Cousins and Earl (1992). It is, however, important to be aware of the limitations of participatory models, for example, the tendency to involve only professionals and do not consider other primary citizens in the evaluation process (see Weiss 1998). The results of participatory models depend on peoples' ways of experiencing or making sense of their worlds, which is contingent on the making up, forming, and organizing their knowledge into distinctive competence in performing their work (Sandberg 2000).

Knowledge-generating evaluation as part of ongoing evaluation contributes to knowledge growth as to clarifying urban project models, testing theory, figuring out how to gauge impacts and outcomes, differentiating between different types of projects, generating lessons learned, and elaborating policy options (Patton 1996). It is associated with conceptual use (Patton 1996), which entails developing better projects in the future, as conceptual use of findings allows using the evaluation to influence thinking about issues in a general way.

Developmental evaluation involves the evolving work of urban projects for continuous improvement (Patton 1996), which can be captured in an ongoing approach to evaluation. However, while such projects often make long-term commitments and do not need to make judgment about continuation, they aspire to continue improving the effort over the long term (Patton 1996). In relation to this, Crossan's (1999) 4I's model (Intuition, Interpreting, Integrating, and Institutionalizing) applies the developmental model of learning where organizational learning moves from the individual level, to group level, and finally to organization level. Creating organizational learning engages people creatively, which leads to more informed stakeholders.

5.7.2.3 Evaluation Challenges of Sustainable Urban Forms

Whether in discourse, theory, or practice, the issue of existing sustainable urban forms as instances of sustainable cities has been problematic and difficult to deal with, and research results tend to be uncertain, weak, limited, divergent, and not conclusive, particularly when it comes to the evaluation of the contribution of such forms to the goals of sustainable development, i.e., the actual effects of the claimed benefits of sustainability (Bibri and Krogstie 2017a). Indeed, although there appears to be in research on sustainable urban forms and anthologies a consensus on topics of relevance to sustainability, it is not evident which of these forms are more sustainable and environmentally sound (Bibri and Krogstie 2017a). A critical review of existing models of sustainable urban form as approaches addressed on different spatial scales demonstrates a lack of agreement about the most desirable urban form in terms of the contribution to sustainability (Jabareen 2006). In fact, it is not an easy task to "judge whether or not a certain urban form is sustainable" (Kärrholm 2011, p. 98). Even in practice, many planning experts, landscape architects, and local governments are—in the quest to figure out which of the existing sustainable urban forms is the most sustainable—grappling more specifically with the dimensions of such forms by means of a range of urban planning and design approaches (Jabareen 2006). In addition, research, whether theoretical or empirical, tends to be scant on evaluating the extent to which existing models of sustainable urban form contribute to sustainability or comparing different models according to their contribution to the goals of sustainable development. The very first endeavor in this direction was Jabareen's (2006) study, an attempt to develop a conceptual framework for assessing the sustainability of four sustainable urban forms: eco-city, compact city, new urbanism, and urban containment, and to articulate the underlying design concepts and principles. Regardless, as a key finding of his study, "neither academics nor real-world cities have yet developed convincing models of sustainable urban form and have not yet gotten specific enough in terms of the components of such form" (Jabareen 2006, p. 48). Furthermore, there is a need for research to address the issue of the evaluation of the contribution of smart sustainable cities to sustainability. To reiterate, Bibri and Krogstie (2017a) present a summary of important knowledge gaps (and challenges) in this regard, as shown in Table 5.2.

5.7.2.4 Urban Simulation Models: Assessing and Optimizing the Contribution of Smart Sustainable Cities to Sustainability

In the context of smart sustainable cities, the modeling and simulation process entails creating and analyzing digital prototypes of physical, infrastructural, environmental, socio–economic, spatiotemporal, operational, and functional models in terms of how they operate, interrelate, and affect one another to identify and predict dynamic changes in the underlying behavioral patterns due to some kind of reciprocal relationships cycling to produce the kind of patterns that smart sustainable cities might exhibit as a result of their functioning, adaptation, and development in relation to sustainability. This allows to determine and forecast potential problems in the real world, and to look at more effective ways to overcome or eradicate them. In this regard and context, complex system modeling and simulation denotes the operation of the whole model of the system (smart sustainable city

Table 5.2 Key knowledge gaps pertaining to the evaluation of the contribution of smart sustainable cities to sustainability

Key knowledge gaps concerning the evaluation of the sustainability of smart sustainable cities
• There is a need for integrating smart methods with the typologies and design concepts of sustainable urban forms to evaluate their practicality as to their contribution to sustainability in the context of smart sustainable cities
• There is no framework to be used as a classification system or ranking instrument against which smart sustainable cities can be evaluated in terms of their smart contribution to sustainability
• There is no assessment framework for measuring how smart targets can enhance sustainability goals
• There is no common conceptual framework for comparing the evolving models of smart sustainable city and planning propositions in terms of their contribution to sustainability
• There is a need for theory for evaluating the extent to which a given model of smart sustainable city contributes to sustainability as to its different aspects
• There is a need for theory for comparing the evolving models of smart sustainable city according to their contribution to sustainability goals and smart targets in an integrated approach
• There is a lacuna in analytical studies for testing propositions about what makes a city smart sustainable
• There are deficiencies in the few models measuring the smartness of smart sustainable cities

and its sub–systems) to evaluate the performance of the system behavior as regards to sustainability, and allows to adjust any parameters within the system under investigation and then to optimize the system to increase success in terms of enhancing different aspects of sustainability across various urban domains (Bibri and Krogstie 2017b). This involves alterations in such domains in terms of operations, functions, designs, services, strategies, and policies, as well as in how these domains interrelate and are coordinated.

There is an evolving immediacy in the building of all kinds of urban simulation models thanks to the recent advances in, and pervasiveness of, sensor technologies and their ability to provide information about medium- and long-term changes in the context of real-time cities (e.g., Bibri and Krogstie 2017a). This involves replacing aggregate models with disaggregate ones while exploring many different kinds of models construction and extending the complexity sciences and thereby diversifying the approach to the construction and evolution of these models (e.g., Batty et al. 2012; Bibri and Krogstie 2016a, 2017b). It is important to construct many different models of the same urban situation, predicted on the assumption that a pluralistic approach is central to improving the understanding of this complexity (Batty et al. 2012). The prominence of urban simulation models in this context lies in aiding urban planners, administrators, architects, and experts in understanding by means of evaluation procedures under what conditions and in what ways urban systems and domains fail to deliver at the level of some dimensions of sustainability and what to do about potentially predicted changes, emergent dynamics, or forecasted problems, e.g., whether there is a need to further enhance the integration and coupling of urban systems or some of their components, to further organize and coordinate urban domains, and/or to create better or merge hitherto unconnected typologies and design concepts across certain spatial scales. In short, the aim is to inform the future design and planning of sustainable cities on the basis of predictive insights and forecasting capabilities in ways that allow to strategically assess and optimize their contribution to the goals of sustainable development.

In relation to existing sustainable urban forms as sustainable city models (Bibri and Krogstie 2017b), the available big data processing platforms, techniques, and algorithms deployed in the urban environment should be able to collect, store, coalesce, integrate, and analyze the urban data to build powerful new forms of urban simulation models, with the primary aim being to gain predictive insights for strategic decision-making and knowledgeable action-taking purposes concerning the operational functioning, planning, and design of such forms. This involves the kind of decisions and actions associated with the strategic assessment and continuous optimization of the contribution of sustainable urban forms to the goals of sustainable development through applying modeling and simulation approaches into rearranging or integrating different typologies and design concepts (e.g., sustainable transport and density, sustainable transport and mixed land use, solar passive design and density, and diversity and green space) across different spatial scales, as well as urban domains (e.g., mobility and transport behavior, land use and transport, energy and the environment, public health care and the environment, and public safety and land use) in an optimal way, with the ultimate aim of enhancing environmental and socioeconomic performances of such forms as complex systems in the context of sustainability. This can be done through simulation and prediction methods built on top of the mined models or patterns resulting from the process of knowledge discovery. In the quest to master the complexity associated with this process in the context of smart sustainable cities for different uses in planning, it is necessary to develop an entirely new holistic system that integrates data collection, mining, and querying, involving all urban domains as well as the ways in which they can be connected, coordinated, and joined together by a web of relationships based on the integration of databases and networks. Currently, one of the most significant challenges for smart sustainable cities is to develop such system in terms of data, patterns, correlations, models, and simulations for relevant domains and their amalgamation in the context of sustainability (Bibri and Krogstie 2017b), to reiterate. In all, urban simulation models are intended to substantiate the practicality of the typologies and design concepts of sustainable urban forms in terms of their sustainability performances, which can be affected by urban growth, urban dynamics, environmental pressures, changes in socioeconomic needs, emerging urban trends, and other external factors. As part of urban intelligence functions, urban simulation models represent new conceptions of the way smart sustainable cities of the future can utilize and combine complexity sciences and data science in developing new powerful methods for generating urban structures and forms that improve sustainability (See Chap. 6 for a general discussion of urban simulation models).

5.8 Investigating and Evaluating the Contribution of Sustainable Urban Forms to Sustainability

5.8.1 Assessment Research Issues in Sustainable Urban Planning

The link between the built environment and human mobility and behavior has long been and continues to be, of interest to the field of sustainable urban planning. However, the direct assessment of such relationship is still rare and largely ignored in the field, but the concepts, theories, and methods used by urban planners provide a foundation for an emerging body of research on this link, which is increasingly burgeoning with the increasing use of big data in urban analytics and planning. This issue constitutes only one strand of research on sustainable urban forms in relation to the evaluation of their contribution to sustainability in terms of environmental and socioeconomic performances (Bibri and Krogstie 2017b). One of the intellectual challenges of smart sustainable cities is the development and implementation of robust assessment approaches and practices (metrics and guidelines as well as methods for their evaluation) to ensure that such cities are actually (intelligently) sustainable (Bibri and Krogstie 2017a, b; Höjer and Wangel 2015). Likewise, to reiterate, one of the most significant challenges in the realm of sustainable urban forms has long been to develop and apply methods for identifying which kinds of solutions (combining design concepts, typologies, infrastructural systems, environmental and urban management systems, environmental technologies, etc.) are needed, and also for evaluating the effects of these solutions in terms of their contribution to the goals of sustainable development based on a systemic perspective (Bibri and Krogstie 2017b). Without evaluative approaches and practices, smart sustainable cities risk becoming no more than just labels (see Höjer and Wangel 2015), just like some sustainable urban forms, which are seen as fallacy of urban planning (e.g., Neuman 2005)—both without validated urban content (Bibri and Krogstie 2016a).

Research efforts in sustainable urban planning have focused on the idea that certain strategies (based on land use and design policies) through which sustainable urban forms can be achieved, such as density, diversity, and mixed land use can be used to increase walking and cycling as well as transit use (Bibri and Krogstie 2017b; Jabareen 2006). The development of appropriate measures for travel and mobility behavior and the built environment is an essential component of this research on urban sustainability (Handy et al. 2002; Jabareen 2006). To provide more conclusive evidence, in addition to the available evidence that lends itself to the argument that a combination of certain typologies and design concepts (density, mixed land use, diversity, sustainable transportation, etc.) helps create lively, healthy, and livable communities by promoting walking and bicycling (Bibri and Krogstie 2017b), researchers must address several issues, including refining measures of the built environment, developing more complete data on walking and bicycling, and spatially matching detailed data on the built environment to detailed data on travel and mobility behavior (Handy et al. 2002). Efforts to characterize and predict the link between the built environment and travel and mobility behavior in the context of sustainable urban forms entails, in addition to developing and evaluating appropriate measures, employing advanced big data technologies as part of urban analytics focused on sustainability issues in relation to planning and design.

5.8.2 Mobility and Travel and New Tools for the Governance of Related Demand

Mobility and travel behavior are core concepts in sustainable transport planning. As such, they are inextricably linked such that the ability for citizens to move from place to place freely and easily occurs through some kind of travel. In more detail, mobility is associated with the whole of trips generated daily by urbanities, and the methods and conditions associated with such trips (modes of transport selected, time spent in transport, destination of trip, etc.). And travel refers to the movement from one place (street) to another, and dissected into the frequency of trip, the trip length, the trip destination, and the mode of travel (e.g., automobile, transit, walking, or cycling), and the trip purpose (e.g., work, shopping, leisure, etc.). One argument regarding mobility is that wide, automobile-oriented streets or -dependent places does not create mobility for all, but actually eliminate mobility for non-drivers. Mobility for all and thus accessibility is rather highest in places that accommodate transit users, pedestrians, and bicyclists as well as drivers. Travel can be analyzed at either the disaggregate level of the individual or the aggregate level of the metropolitan area or traffic analysis zone (e.g., Handy et al. 2002), just like mobility in terms of individual and collective patterns (e.g., Batty et al. 2012). Disaggregate data are better suited for the purpose of studying the link between certain typologies of the built environment (e.g., density, mixed land use, diversity, green space, and sustainable transportation) and travel behavior because they enable more sophisticated behavioral modeling in addition to their availability for most major metropolitan areas through typically regional travel diary surveys.

In relation to traffic, instead of basing transportation networks on equilibrium conditions with small variations, "new data can help us understand whether or not the real urban traffic can be considered an equilibrium system with respect to a cost function, how people really make choices and how these choices affect the development and spreading of congestion in the networks. The large number of trajectories and disaggregated traffic data from cities of different sizes and in different locations globally will provide a unique way to identify the macroscopic observables and control parameters that affect individual decisions and integrate them in agent-based models. Current day-to-day traffic assignment models are not suitable for modeling the traffic evolution under strong changes of network topology (e.g. a heavy disruption or a new mode of transport such as that occurring in many cities in developing countries because such models assume that drivers build on their experiences from past days. But when significant network changes occur, lack of observation measurements do not allow for the realistic modeling of pattern evolution and identification of equilibrium or non-equilibrium" (Batty et al. 2012, p. 489).

Advanced GPS technologies enable to record individual mobility (drivers) data across an entire urban network, providing information on single trajectories with a spatial scale of certain number of km and a certain timescale from seconds to hours, in addition to other features, such as position, speed, motion direction, GPS quality, and travel velocity in the network. The emergence of big data pertaining to mobility and data-driven urban analytics opens unique opportunities that use microscopic mobility data to understand and analyze the human decision mechanisms in the context of sustainable urban forms in terms of the features and scales associated with the built environment in terms of urban design, land use, and transportation systems. For example, "macroscopic laws will be the starting point of a new generation of microscopic models based on individual mobility demand, and will enable us to perform a real-time reconstruction of the traffic state across the whole urban network (nowcasting), to integrate the private mobility with the public mobility realizing low energy sustainable transportation policies, and to predict future scenarios simulating emerging crisis events… Our aim is to generate an entire research dimension with respect to the role of failsafe mechanisms which pertain to crises that are generated by problems of mobility" (Batty et al. 2012, p. 504). Also, big data analytics and related models and simulation methods can be useful in investigating the crowd dynamics (e.g., the intentional dynamics of travelers) using microscopic approach, e.g., showing pedestrian flow reconstruction via GPS measures, which is important to understand human mobility behavior and related issues (see Batty et al. 2012).

5.8.3 The Untapped Potential of Big Data Analytics in Urban Design and Planning

ICT can provide unparalleled (data-driven) methods that enable to monitor, understand, and analyze complex urban phenomena, dynamics, and changes in the context of sustainable urban forms. This is invaluable for evaluating, forecasting, and thus planning and designing such forms, in particular in relation to increasing and sustaining their contribution to the goals of sustainable development. In view of that, in addition to its key role in significantly improving this contribution through novel applications (see Chap. 9 for specific application examples), big data analytics holds great potential to assess the extent of this contribution by substantiating the practicality of the different typologies and design concepts of sustainable urban forms, as well as to generate simulation models necessary for gaining predictive insights into the progressive and shifting patterns of this contribution that can aid in making strategic decisions based on forecasted future changes and problems, as discussed above. Modern urban ICT, as a by-product of its normal operation—on the basis of big data analytics and what it entails in terms of pervasive sensing, data processing, cloud computing, and wireless and mobile networking—allows for collecting, storing, and integrating massive repositories of spatiotemporal data pertaining to urban structures, organizations, and forms. Such repositories can be utilized for monitoring, understanding, evaluating, and planning sustainable urban forms in ways that strategically evaluate and optimize their contribution to sustainability. Especially, the issue of the evaluation of such forms has been, and continues to be, one of the most significant research challenges in the realm of sustainable urban forms, to reiterate. Unsurprisingly, big data movement is gaining increased momentum and worldwide attention in the domain of urban sustainability (Al Nuaimi et al. 2015; Bibri and Krogstie 2017a, b). This is being fueled and boosted by the intensive R&D within a wide variety of data science and computer science areas in academic circles as well as in the industry, with huge expectations for further innovations or breakthroughs related to big data analysis and management practices. The rationale for this pursuit is the underlying benefits of the striking analytical power of big data analytics in relation to the different dimensions of the sustainability of cities, among other things.

5.8.4 An Alternative to Traditional Data Collection and Analysis Methods for Investigating Sustainable Urban Forms

In addition to its uses in the systems and domains of sustainable urban forms to enhance processes, practices, and services, big data analytics can accelerate and improve the way data can be collected, processed, analyzed, modeled, and simulated in the research domain of urban sustainability, especially in relation to investigating and evaluating to what extent sustainable urban forms contribute to the goals of sustainable development and what can be done to strategically increase this contribution (e.g., using novel applications, creating whole new urban forms, and/or combining existing or developing alternative design and planning principles depending on different spatial scales). As an alternative to traditional data collection and analysis methods, which have been used for over two decades or so to study sustainable urban forms, big data analytics driven by the IoT and UbiComp is changing the whole research and scientific development paradigm, shifting from collecting data manually and examining and reflecting on these data to relying on automated sensing of data and advanced analytics, in addition to using powerful forms of modeling, simulation, and prediction. With that in mind, big human mobility data can, for example, "be used to overcome the limits of surveys, namely their high cost, infrequent periodicity, quick obsolescence, incompleteness, and inaccuracy" (Batty et al. 2012, p. 489), as well as the constraints and biases associated with case studies and related data collection methods, such as interviews, examination of manual documents, and participatory and nonparticipatory observations. These issues have in fact long affected the robustness and reliability of research results (findings, generalizations, theories, etc.) within the field of urban sustainability or sustainable urban planning, which have in turn impacted on urban practices in terms of the application of the principles of sustainability in the urban domain. Many studies investigating, or referring to other research work carried out on, the correlation between travel behavior (walking, cycling, car driving, transit use, etc.) and other determinants or indicators of environmental performance, on the one hand, and density, compactness, diversity, mixed land use, and other design concepts through which sustainable urban forms can be achieved, on the other hand, point implicitly or explicitly to the disadvantages of the traditional data collection and analysis methods in terms of how they negatively affect the value of the obtained research results (Bibri and Krogstie 2017b). These studies tend to generate non-conclusive, weak, limited, unreliable, conflicting, or uncertain findings (e.g., Bibri and Krogstie 2017b; Jabareen 2006; Kärrholm 2011; Neuman 2005).

5.8.5 The Role of Big Mobility Data in Evaluating Sustainable Urban Forms

Evaluating and forecasting the built form (buildings, streets, residential and commercial areas, public and green infrastructure, neighborhoods, etc.) of cities are at the core of urban planning and design. This pertains in this context to the typologies and design concepts of sustainable urban forms as set of organized, coordinated, and standardized physical arrangements and spatial organizations, as well as to their strategic contribution to the goals of sustainable development.

5.8.5.1 On the Link Between Big Mobility Data and Environmental Performance

The role of big mobility data is undoubtedly pivotal in understanding and assessing the relationship between the individual and collective mobility patterns and the environmental performance assumed to be achieved through the typologies and design concepts of sustainable urban forms. Specifically, big mobility data analytics provides unsurpassed ways to learn about and substantiate the extent to which this performance is impacted by the mobility patterns that result from, or are shaped by, the spatial and urban proximity, contiguity, agglomeration, and/or connectivity underlying the respective typologies and design concepts—thanks to the more effective evaluation approaches enabled by big data analysis and management models using heterogeneous and distributed sources of urban data. These novel assessment practices can provide novel insights into and robust results regarding the extent to which sustainable urban forms contribute to the goals of sustainable development. Currently, there is conflicting evidence on the relationship in question due to the challenge of collecting, integrating, managing, and analyzing real-time mobility data and data from large-scale datasets that can simultaneously record, calibrate, and visualize environmental performance determined by the levels of GHG emissions deriving from energy consumption related to dynamical traces of different kinds of mobility and travel behavior in relation to the typologies and design concepts of sustainable urban forms and their combination across various spatial scales in different locations. In addition, our knowledge of the interplay between individual and collective mobility and environmental performance is limited, partly due to the difficulty in collecting, integrating, managing, and analyzing large-scale data that simultaneously record dynamical traces of individual and collective movements and energy consumption levels across different spatial and temporal scales. To reiterate, many studies, which have attempted to find correlations between environmental sustainability and the typologies of sustainable urban forms or to effectively measure the actual effects of the claimed benefits of sustainable urban forms from an environmental perspective, tend to generate uncertain, weak, limited, and sometimes conflicting findings on such correlations (see, e.g., Bibri and Krogstie 2017b; Jabareen 2006; Neuman 2005; Williams et al. 2000).

5.8.5.2 On the Link Between Big Mobility Data and Socio(-economic) Performance

By the same token, big mobility data analytics can be instrumental in understanding and assessing the relationship between the individual and collective mobility patterns and the socioeconomic performance assumed to be achieved through the typologies and design concepts of sustainable urban forms. In a similar vein, big mobility data analytics provides unparalleled means to learn about and substantiate the extent to which this performance is impacted by the mobility patterns that result from, or are shaped by, the spatial and urban proximity, contiguity, agglomeration, and/or connectivity underlying the typologies and design concepts of sustainable urban forms. The socio-spatial fabric of sustainable urban forms entails diverse spaces across multiple spatial scales and numerous multilayered, intertwined networks of dynamic relations between people, communities, organizations, and institutions, as well as the way such forms are spatially arranged and socioeconomically structured. Understanding how these coupled, coordinated networks are organized and how this organization evolves in urban spaces in the context of sustainable urban forms is key to understand how well such forms perform on the socioeconomic scale with respect to the underlying typologies and design concepts.

Among the many complex questions that are barely explored to date is the extent to which the individual mobility patterns shaped by density, compactness, diversity, and mixed land use as characteristic features of sustainable urban forms do impact or are associated with the structure of social networks (sustaining long-lasting friendships, establishing new social and professional links, initiating face-to-face conversations, etc.). What is known thus far is that "social links are often driven by spatial proximity, from job- and family-imposed programs to joint involvement in various social activities" (Batty et al. 2012, p. 490). Of relevance to highlight here is that social interactions relate to improving the quality of urban life, a yardstick by which a city as an urban form can be evaluated against its livability and sustainability. A key theme in debates on compactness and diversity is the promotion of the quality of life through social interactions (Wheeler 2002; Williams et al. 2000). In light of this, big mobility data analytics can play an important role in understanding complex urban phenomena and dynamics related to other aspects of the built environment as to urban design, land use, and transportation system favored by sustainable urban forms. In parallel, research within the area of big data analytics pertaining to social networks should extend its focus beyond the social space to include questions of multifaceted nature and thus other kinds of spaces. The psychology behind transport behavior is an example of related work (Schnfelder and Axhausen 2010). Also, the patterns of mobility or forms of transport driven by some typologies are most likely to correlate with some aspects of social networks and links driven by such factors as urban contiguity, agglomeration, and connectivity. Moreover, traffic modes enabled by some typologies are most likely to significantly vary from one day to another (or other timescales) and from one location to another despite the similarity of demand profiles driven by how transport systems and networks are connected with the different typologies of sustainable urban forms. Currently related explanations are extremely weak and future ICT is expected to provide dramatically new datasets and predictive models that will disentangle many intractable issues concerning the link between different forms of mobility and transport and socioeconomic performance specific to the typologies and design concepts of sustainable urban forms. How urban topographic and design characteristics and related planning tools affect choices of people in terms of travel mode, behavior, and route, and how this in turn affects social structures and economic networks is one of the significant intellectual challenges to address in the realm of sustainable urban forms.

From a general perspective, "our knowledge of the interplay between individual mobility and social networks is limited, partly due to the difficulty in collecting large–scale data that simultaneously record dynamical traces of individual movements and social interactions" (Batty et al. 2012, p. 491). This is of high pertinence to some of the typologies of sustainable urban forms as well, as they seek to promote this kind of shared social foci as part of enhancing the quality of life, as pointed out above. Regardless, addressing the interplay in question requires not only the ubiquity of mobile phones and mobile networks, but also advanced wireless communication networks for collecting mobile communication detail records and the GPS and RFID tracks as individual mobility patterns and dynamical traces of social interactions; mobility patterns based on localizations in space and time; remote sensors for tracking body movements; social connections and other types of networks; and so on. The accessibility to and effective use of these massive data repositories hold tremendous potential to develop advanced and sophisticated (dynamic) models of human mobility in relation to the typologies of sustainable urban forms characterized by such features as fidelity with real-world phenomena, comprehensiveness, consistency, and robustness. The predictability of these models is of utmost importance to the strategic planning of sustainable urban forms and the combination of the underlying typologies and design concepts in relation to different spatial scales in terms of the associated socioeconomic (and environmental) performance in the context of sustainability. Indeed, these models as representation of operating and organizing processes of urban life on a small or medium scale allow urban administrators to describe important phenomena in urban life and to predict how changes in such processes would affect other parts of urban systems in terms of their operational functioning.

5.9 Wicked Problems and the Role of the Uses of Big Data in Urban Design and Planning

The fundamental opportunities and challenges of the uses of big data in smart sustainable cities have, albeit their appeal, not been sufficiently systemized and formally structured. In particular, the necessary conditions for the strategic application of big data in such cities as an evolving techno-urban phenomenon and thus a relatively new concept (Bibri and Krogstie 2016a, 2017a) need to be spelled out and their limitations must also be anticipated and elucidated. There are different ways to address these and other important questions in light of the current interdisciplinary knowledge of the field of smart sustainable cities (e.g., see Bibri and Krogstie (2017a) for an overview). In this line of thinking, Bettencourt (2014) attempts to answer some of these questions by formalizing the use of data in urban policy and planning in light of the conceptual frameworks of engineering, and shows that this formalization enables to identify the necessary conditions for the effective use of data in policies that address a large array of urban issues. This is intended to demonstrate that big data technologies as a strand of modern ICT are providing new opportunities for the application of engineering solutions (based on data science) to smart sustainable cities.

But the problems of smart sustainable cities are primarily about citizens. Environmental, economic, and social (and sometimes infrastructural and physical) issues in contemporary cities define what planners call “wicked problems” (Rittel and Webber 1973), a term that has gained currency in urban planning and policy analysis, especially after the inception of sustainable development in the early 1990s. These kinds of problems are not expected to yield to engineering solutions for specific reasons (Rittel and Webber 1973) that break the assumptions of feedback control theory (Astrom and Murray 2008). Bettencourt (2014) addresses the issue of wicked problems in light of computational complexity theory, drawing on More and Mertens (2011), to formally argue that comprehensive or detailed urban planning is computationally intractable. This signifies that solutions entailing the knowledge and prediction of chains of detailed behaviors in smart sustainable cities as complex systems have the basic property that they become practically impossible, irrespective of the scale and diversity of data available, and this "clarifies the central dilemma of urban planning and policy: planning is clearly necessary to address long-term issues that span the city…and yet the effects of such plans are impossible to evaluate a priori in detail" (Bettencourt 2014, p. 13), although they are informed by established knowledge and solid theoretical foundations (e.g., sustainability science, systems science, and complexity science). The urban world is constantly changing, intrinsically unpredictable, and infinitely rich.

For example, a wicked problem in the context of sustainable urban forms relates to what Kärrholm (2011) describes as dynamic and multi-scalar approach in urban planning and design. This involves attempting to solve a problem at a certain scale may improve the situation (e.g., positive sustainability effects) at that scale but can have adverse effects on a larger or another scale. The contradictions pertaining to sustainability go deeper still, as the same effort might increase environmental sustainability on one scale (e.g., the metropolitan), while decreasing economic sustainability on another (e.g., the neighborhood). To address this wicked problem, Kärrholm (2011) sheds light on tendencies toward scale stabilization, i.e., the tendencies of planning from the perspective of a few pre-fixed scales, and views scales as effects of processes and activities of the lived environment. His view implies that the effects contributing to the goals of sustainable development are always enacted at different spatial levels in terms of dimension and size, thereby their multi-scalar nature, a proposition that is supported by the premise that urban forms participate in the production of effects on different scales. In other words, the outcome of discussing the effects of a certain scale (e.g., the neighborhood) is certainly different from the perspective of another scale (e.g., the metropolitan, the city, the motorway system, the cycleway system, or the local street).

In order to yield the most effective sustainable effects, taking scales—e.g., the street, the neighborhood, the district, and the city—is of high relevance to the implementation and integration of design concepts of sustainable urban forms, such as density, diversity, mixed land use, and passive solar design. The same goes for building new neighborhoods or blocks in terms of how their spatial structure affect everyday life on the street, social interaction, walking and cycling, and access to green space, as well as the role they play on different scales. Given the complexity of urban system, most of environmental, economic, and social problems are of an ill-structured nature as they do not yield a right answer or one solution for they mirror real-world situations where issues and views tend to be conflicting, plural, and contentious. The underlying assumption is that the integration of environmental, economic, and social sustainability is contradictory, as different dimensions of sustainability rely on different criteria for success, which tend to be usually conflicting. Sustainable urban development is characterized as achieving a balance between the development of and equity in the urban areas and the protection of the urban environment. However, the conflicts among sustainable development goals are very challenging to tackle and daunting to overcome. This has indeed been, and continues to be, one of the toughest challenges facing urban planners and scholars as to decision-making and planning in the realm of sustainable urban forms (Bibri and Krogstie 2017a), as well as smart sustainable cities in terms of the associated multidimensional risks they pose to environmental sustainability due to the ubiquity and massive use of ICT (Bibri and Krogstie 2016a). Despite sustainable urban development seeking to provide an enticing, holistic approach into evading the conflicts among its goals, these conflicts "cannot be shaken off so easily," as they "go to the historic core of planning and are a leitmotif in the contemporary battles in our cities," rather than being "merely conceptual, among the abstract notions of ecological, economic, and political logic" (Campbell 1996, p. 296). As a consequence, planners will in the upcoming years "confront deep-seated conflicts among economic, social, and environmental interests that cannot be wished away through admittedly appealing images of a community in harmony with nature. Nevertheless, one can diffuse the conflict, and find ways to avert its more destructive fall-out" (Campbell 1996, p. 9). Using big data in urban analytics as part of engineering solutions for advancing urban sustainability planning is a way of attempting to avert the destructive fallout of the conflict in question.

Based on the above reasoning, there is no perfect solution to urban sustainability problems in terms of planning and design, and each set of identified solutions would contain strengths and weaknesses. The difficulty in formulating the right solutions to wicked/ill-structured problems encountered by urban planners and administrators lies in the chaotic nature of multiple cause and effect relationships and the way they shape the patterns of behavior of cities. In view of that, sustainable urban planning and design is required to examine problems from different angles and find the best possible solutions. In this regard, "relatively simple-minded solutions, enabled by precise measurements and prompt responses, can sometimes operate wonders even in seemingly very complex systems where traditional policies or technologies have failed in the past" (Bettencourt 2014, p. 14). To put it differently, relatively simple solutions with no great intelligence involved can, under specific circumstances, solve very challenging problems. One manifestation of this has to do with using fast and precise enough measurement and adequate simple reactions instead of applying smart approaches. This is the logic of feedback control theory as part of modern engineering (Astrom and Murray 2008). In view of that, knowing the desired operating point for a system and having the means to operate on the system, while observing its state change via feedback loops, can enable to turn it into a simple problem under general, crucial conditions that can measure and recognize potential problems, just as they start to arise and act to make the necessary corrections (Bettencourt 2014). In this context, the crucial issue is that of temporal scales, which are at the core of big data and their use in urban planning in terms of short-term thinking about how smart sustainable cities can function and be managed; every urban system has intrinsic timescales at which problems develop—minutes, hours, days, and decades. Cycles of measurement and reaction must act well within this window of opportunity to avoid such complex problems by simple means (Bettencourt 2014).

It is conspicuous now that the emergence of urban big data may offer radically novel solutions to difficult urban sustainability problems. Modern ICT is now so fast in comparison to most physical, environmental, social, and economic phenomena that myriads of important urban planning and policy problems are falling within this window of opportunity (see Bettencourt 2014). In such circumstances, models of system response enabled by big data analytics (see Chap. 4 for a discussion of deployed data mining results as part of diverse solutions to urban sustainability problems) can be very simple and crude and typically be linearized (see Astrom and Murray 2008).

Thus, the analytical engineering approach conveniently bypasses the complexities that can arise in the systems of smart sustainable cities at longer temporal or larger spatial scales. The potential miracle of big data in such cities lies in essentially solving difficult and important urban sustainability problems without theory. Many examples of urban planning, management, and policy in smart sustainable cities that use data successfully can have this flavor, irrespective of whether their implementation involves organizations or computer algorithms. Table 5.3 presents a summary of key urban sustainability issues, where we attempt to roughly characterize their typical temporal and spatial scales and the nature of their operating points, or outcomes.

For example, considering urban transportation systems, e.g., a bus network, "buses should carry passengers who wait a few minutes to be transported over a few kilometers. Measuring the time in between buses at each stop, possibly together with the number of passengers waiting, gives the planner the basis for a feedback control solution: Communicate with buses to enforce desired standards of service, quickly place more or fewer units in service where these parameters start to deviate from the ideal metrics, and the quality of service as measured by per person waiting times will improve. This type of strategy can be operated intuitively by human

Table 5.3 Urban sustainability issues, their temporal and spatial scales, and the character of their associated metrics

Problem	Timescale	Spatial scale	Outcome metrics
Transportation (buses)	Minutes	Meters	Simple
Infrastructure (roads, bridges, cables)	Days	Meters	Simple
Traffic	Minutes	Meters to kilometers	Simple
Mobility	Days	Kilometers	Simple
Energy and environment	Years	Citywide	Complex
Education	Decades	Citywide	Complex
Health care	Years	Citywide	Complex
Economic development	Decades	Citywide	Complex
Land use	Decades	Citywide	Complex

Source Adapted from Bettencourt (2014) dispatchers but possibly can also be implemented automatically by an ICT algorithm 38 with access to the necessary measurements and actions. Feedback control theory provides the framework for the development and optimization of any of these solutions" (Bettencourt 2014, p. 15). Other similar strategies can be applied to reduce GHG emissions and traffic congestions.

Similar procedures could be devised for power supply management, traffic management, water and waste management, mobility, land use, and so on. These could also generally be integrated together in relevant ways. While progress in some urban sustainability problems is fundamentally an ICT problem (big data analytical solution), enabled by simple actions, strategies, or policies that nudge the states of urban processes toward optimal performance, other urban sustainability issues, especially those that are primarily environmental and social, acquire a different character due to their ill-(or not well-)defined operating points and the diffused nature of their dynamics as well as playing out over large temporal or spatial scales. Thus, it has remained challenging to develop engineering solutions (analytical procedures) to problems of sustainability aspects involving health care, energy and environment, land use, and economic development on the city or regional scale. Therefore, there has been growing recognition that health care, for example, should involve advanced analytics to interpret vast amounts of data to improve healthcare outcomes. Some health issues (diseases) "are often characterized by simple metrics and by local processes of social contact between individuals," but health "conditions that play out over longer times and possibly have more complex and diffuse social causation…have proven far more difficult" (Bettencourt 2014, p. 15).

Therefore, the simplicity of performance metrics expressed as objective quantitative quantities relative to the properties of the controlling system—the policymaker or the algorithm—such as their response times, and the knowledge of their proximate causes in space and time are the crucial conditions for successful analytical solutions inspired by engineering (Bettencourt 2014). Accordingly, big data analytics as a set of technological and scientific processes become of importance for achieving progress through the increasing automation of solutions to intractable environmental, social, and economic sustainability problems in smart sustainable cities. While the physical aspects of such cities seem at first sight manageable through engineering practices, their social, environmental, and infrastructural aspects may become entangled over the long run.

The essential character of wicked problems Rittel and Webber (1973) is that they cannot be solved in practice by urban planning. The authors argue that the planning problem has two distinct aspects: (1) the knowledge problem and (2) the calculation problem. The first problem refers to the data needed to map and understand the current state of the smart sustainable city. It is conceivable that urban life and physical infrastructure could be adequately sensed in several million places at fine temporal rates, generating huge but manageable rates of information flow by advanced ICT. It is not impossible, albeit still implausible, to conceive advanced ICT that would enable access to detailed information about every aspect of the infrastructure, services, social lives, and environmental states in a smart sustainable city. The second problem refers to the computational complexity to carry out the actual task of planning in terms of the number of steps necessary to identify and assess all possible scenarios and choose the best possible course of action. Unsurprisingly, the exhaustive approach of assessing all possible scenarios in a smart sustainable city is impractical due to the fact that it entails the consideration of impossibly or unreasonably large spaces of possibilities. For the formalization of this statement in the form of a theorem and related mathematical details and the sketch of a proof, the interested reader is directed to Bettencourt (2014). Given the proviso of some stipulations and limitations, it can be demonstrated that the planning of smart sustainable cities in detail is computationally impossible. This shows that the use of complex models (Portugali 2011) in the detailed planning of such cities has its limits and cannot be exhaustively mapped and solved in general, irrespective of how much urban data may be available for urban planning purposes, to reiterate. Here comes the role of big data analytics in smart sustainable cities and thus conceiving of related planning under the stipulations and limitations in question. The key is the nature of self-organization of environmental, social, and economic life in smart sustainable cities and the development of a general quantitative understanding of how such operating and organizing processes function in such cities as vast networks across diverse domains and sub-domains, spanning large spatial and temporal scales, to draw on Bettencourt (2014). The development of the urban theory recognizing that individual details are of irrelevance to characterizing complex systems as a whole while identifying general dynamics follows from increasing urban data availability from around the world in terms of observations and from experiments (Bettencourt 2014). In all, the “dilemma between the need for planning and coordination and its impossibility in detail is resolved by the recognition that cities are first and foremost self-organizing social networks embedded in space and enabled by urban infrastructure and services. As such, the primary role of big data in cities is to facilitate information flows and mechanisms of learning and coordination by heterogeneous individuals. However, processes of self-organization in cities, as well as of service improvement and expansion, must rely on general principles that enforce necessary conditions for cities to operate and evolve. Such ideas are the core of a developing scientific theory of cities, which is itself enabled by the growing availability of quantitative data on thousands of cities worldwide, across different geographies and levels of development” (Bettencourt 2014, p. 12), including sustainable development. These three uses of big data and ICT in smart sustainable cities constitute then the necessary pillars for more successful urban policy, management, and planning that promote and strengthen the fundamental role of such cities as enabling arenas for sustainable development goals and engines of sustainability innovation in human societies.

5.10 Urban Big Data and Sustainable Development Indicators and Targets: Opportunities and Challenges

Big data innovations are opening new opportunities for developing novel urban-level metrics for monitoring the goals of sustainable development. The aim of this monitoring, which occurs through objective indicators and targets based on common denominators in the ability to collect, coalesce, and maintain relevant standardized data is to harmonize those goals at the national level (Kharrazi et al. 2016). The evolving urban big data as part of the emerging smart sustainable cities are advancing the development of scientifically grounded indicators and objective targets in relevance to the goals of sustainable development. The aim is to be able to monitor progress, implement strategies, allocate resources, and increase the accountability of stakeholders (Glaser 2012). This relates to the approaches into operationalizing sustainability, which are conceived based on the design and development of a wide variety of indicators to observe, measure, and assess states over many scales and in different contexts in an effort to support the transition toward sustainable development. Indicators can be defined as variables, operational representations of a characteristic, property, or quality as attributes of a system (Bibri 2013). They depict our image of an attribute of system defined in terms of a specific measurement (Gallopín 1997). For a comprehensive overview of the main sustainability indicators, the interested reader might want to take a look at Modlan and Billharz (1997).

While there is broad consensus on the need for indicators and targets, they are still under discussion to agree on their exact definitions and entailments by the international community. Indeed, sustainability indicators have particularly been subject to criticism, despite their importance to enable the sustainability principles to function in real-world politics and be operationalized across different nations. As argued by Bibri (2013, p. 74), "applicable to all sustainability indicators, it is a no easy task to gather and determine the data necessary to actually measure the environmental indicators…once established with respect to urban sustainability planning. Moreover, the contested nature of the approach to the sustainability concept has direct consequences on the researchers involved in the creation of sustainability indicators. As a corollary, researchers may work with a perspective different from that on the basis of which the indicators have been created." Different researchers define their indicators in ways that provide arguments to support their approach to defining the sustainability concept and their related goals (Kasemir et al. 1999). In fact, the lack or absence of a more universal definition of sustainable development has given rise to multiple interpretations and philosophical underpinnings, which has led to an explosion of environmental, social, and economic indicators (Bibri and Krogstie 2017a). Besides, Foster (2001, p. 157) argues that "indicators do not read themselves—nor do they simply *register* whether particular forms of development are 'sustainable' or not…The processes of constructing and interpreting them rely on collaborative judgment—and this has to be exercised in a variety of relevant ways, as regards for instance the trustworthiness of the institutions involved, the acceptability of the assumed scientific framings, and validity of the various statistical measures in relation to people's lived experience." As a result, Ortega-Cerdà (2004, p. 10) contends that their success has up till now been "very limited, as many subjective choices are made in the aggregation procedure needed for the creation of these aggregated indicators. As a consequence, they are not perceived as 'objective' and their capacity to be a link between the scientific discourse and the sustainability discourse is lost. We can see, therefore, that the 'perception of objectivity' is a key element in the use of sustainability indicators." Thus, there are doubts surrounding the relevance of indicators, the assumption that the use of such indicators will influence decision-making pertaining to urban planning (Bibri 2013).

In the domain of urban sustainability, assessment frameworks are used to support decision-making in urban planning and development, as they entail methodologies and tools that sustainable cities rely on to show, evaluate, and improve their progress toward sustainability goals. There are many urban sustainability assessment frameworks in the literature. But we only address the widely used and well-known performance measurement systems. Urban monitoring started in the early 1990s after establishing numerous (environmental) indicators to monitor sustainability of urban areas (Marsal–Llacuna et al. 2015), a few years after the widespread diffusion of the concept of sustainable development. The multiple indicators for measuring the quality of life appeared in the 2000s (Mercer 2014). Worth pointing out is that the explosion of indicators has been triggered by the multiplicity of interpretations of sustainable development and the widely varied approaches to its operationalization. However, urban sustainability indicators have been produced by environmental consultancy, sustainable capitalism, research, and green citizenship organizations (Ahvenniemi et al. 2017; McManus 2012). Accordingly, urban sustainability assessment tools have been developed top-down by expert organizations. However, a number of scholars (e.g., Berardi 2013; Robinson and Cole 2015; Turcu 2013) advocate the integration of citizen-led, participatory, and localized approaches. This is anchored in the underlying assumption that the relationships between urbanites, their activities, and the environment must be better understood in order to achieve the required level of sustainability in terms of the integration of its dimensions.

Sustainability indicators are used by public administration and political decision-makers to confirm whether cities implement sustainable development strategies by enabling the assessment and monitoring of urban activities (Tanguay et al. 2010). However, Huang et al. (2009) note that they are associated with shortcomings, as they do not provide normative indications as to the direction to pursue, in addition to not reflecting systemic interactions, to relate to the above discussion. Furthermore, the performance assessment tools are intended for ranking sustainable cities or for allowing cities to find best practices and compare best solutions (Ahvenniemi et al. 2017). There exist diverse approaches to urban sustainability, thereby the diversity of performance assessment tools. In particular, a large number of environmental assessment tools have been developed for various urban domains. There are tools that measure the built environment, ranging from buildings to neighborhoods and districts, in addition to public transportation and services (Haapio 2012). Sharifi and Murayama (2013) provide some well-known neighborhood sustainability rating tools. Other assessment tools have been developed to help urban planners to assess the energy efficiency of a detailed city plan as regards to energy demand of buildings, transport systems, energy systems, and energy sources (Hedman et al. 2014). Of importance to underscore is that existing sustainability performance assessment tools put a much stronger focus on environmental indicators (Berardi 2013; Robinson and Cole 2015; Tanguay et al. 2010) compared to social and economic indicators. For instance, the most well-known sustainable neighborhood rating schemes assign very low weight (about 3% for economy and 5% for well-being) to direct economic and social measures (Berardi 2013). In addition, existing sustainable design approaches have been criticized for solely focusing on reducing harm to the environment (Cole 2012; Reed 2007).

As a consequence, Robinson and Cole (2015) have called for the more integrative and holistic concept of regenerative sustainability. Besides, cities should be seen as urban ecosystems that comprise interactions between the physical, social, and ecological components (Nilon et al. 2003). The physical component is associated with urban morphology (urban forms, spatial configurations, integration values, etc.), a field of study that is concerned with the spatial structures, organizations, and characteristic features of cities. The spatial distribution of activities, efficient use of resources, and accessibility of different services and facilities are crucial aspects of sustainable cities in terms of urban forms, operations, functions, and services, as well as their interconnections (Bourdic et al. 2012; Salat and Bourdic 2012).

The ongoing debate over sustainability indicators point to the need for, among other things, finding the most common denominators in the ability to collect and maintain standardized and globally comparable data relevant to the goals of sustainable development, to analyze such data using advanced big data analytics techniques (e.g., statistics, data mining, and regression analysis), and to adapt them to local contexts by balancing their feasibility based on local practices. However, due to the difficulty surrounding the achievement of universally practiced data and standards due to a range of practical discrepancies and capacities among countries, the UN has called for a “data revolution” for strengthening statistical systems to collect high quality and robust data on urban, regional, and international scales to ensure the monitoring of the goals of sustainable development (Kharrazi et al. 2016). This requires leveraging the emergence of big data innovations across the urban world for meeting the demands of the indicators and targets of sustainable development.

The emergence of urban big data is opening unique opportunities to develop and advance big data practices in terms of more innovative urban indicators and targets of relevance to sustainable development, and thus to leverage big data innovations and leapfrog complex challenges pertaining to diverse urban issues associated with broader sustainability goals. This can be accomplished by various means and endeavors. One endeavor to leverage big data innovations and overcome complex challenges pertaining to diverse urban issues associated with broader sustainability goals is to advance the culture and common skills sets for applying and using urban big data (Kharrazi et al. 2016). While the transition to smart sustainable cities requires a two-pronged approach in terms of governance: top-down and bottom-up, it is fundamentally flawed to pursue a top-down approach when it comes to the development of urban big data. From a transition governance perspective (e.g., Bibri 2015), government-led approach remains determining in building the foundations of and governing the shift to socio-technical transitions, but as regards to big data development and its relation to sustainable urban transformation, this approach risks knowledge asymmetries between local governments and communities and large corporations. Indeed, the bottom-up (citizen- and community-driven) approach is essential to understand how the application of variables relevant to urban sustainability is initiated from the bottom-up, through the engagement of citizens, especially innovation initiatives grounded in this approach are useful where often the top-down approach may struggle to engage its (big data) technology users. In this respect, the role and responsibility of the government lie in promoting and stimulating bottom-up innovation through big data by providing the needed ICT infrastructure. This entails devising and implementing a set of measures in the form of innovation laboratories, living labs for co-design in relation to big data technologies and their use, exploratory activities, experimentation and evaluation of creative ideas and concepts, as well as testing big data techniques and systems in various real-life usage scenarios. This is about empowering citizens through community-led initiatives that may have intrinsic or diffusion benefits toward sustainable change (Seyfang and Smith 2007). In this regard, of utmost importance is to encourage research on the public policy dimensions of this topic—especially on the accessibility of data analytics technology and the active participation of citizens. Such research is critical in the democratic involvement and inclusion of citizens in decision-making and essential to applying big data for urban sustainability. Urban big data should be developed to advocate pluralism and to build what Helbing and Pournaras (2015) identify as digital democracies. A pluralistic approach plays a key role in advancing broad, diverse, and crowd-sourced indicators (Fluckiger and Seth 2016), which can aid citizens in measuring and comparing their progress as to tackling the challenge of urban sustainability. Indeed, developments in rather focussed crowdsourcing are causing new models of scientific discovery to emerge, which are applicable to how we might figure out good designs for efficient and equitable cities (Nielsen 2011). However, policymakers are required "to address common skill sets required by urban citizens. Specifically, how can cities ensure people have the knowledge and capacity to fully participate and benefit from these innovations? Furthermore, research needs to address the accessibility and affordability of these innovations so that vulnerable citizens are not inadvertently disadvantaged or excluded" (Kharrazi et al. 2016, p. 4).

Another endeavor is to invest in research activities and education programs focused on urban big data in terms of technology and analytics in relation to the domain of urban sustainability and its planning. In this context, the emergence of urban big data should be approached through what Ciborra (2004) terms the lens of "hospitality", a lens through which we can alien affordances of urban big data and embrace and implement their advantages and better understand their disadvantages, among other things. It is in research institutions and universities where this hospitality can best be achieved, and which can use and explore smart sustainable cities as laboratories of innovation (see Bibri and Krogstie 2017a). These research and educational entities are well positioned to readily host the emergence of urban big data, and seek innovative solutions and sophisticated approaches of relevance to the challenge of urban sustainability with regard to developing new metrics for measuring and new methods for assessing the urban progress toward sustainable developmental targets in the context of smart sustainable cities. Again, government can have a key role in mainstreaming urban big data technologies and applications by accumulating and preserving the related body of knowledge as well as disseminating and imparting their principles. This is typically carried out inside centers for research and innovation and higher educational institutions, and as part of specific research areas pertaining to urban analytics, smart urban planning, urban informatics, applied urban science, and urban computing. In the face of it, the interest in urban big data has already started to spill out into the wider sustainable urban planning, and initiatives intended specifically to support and foster smart sustainable urban development are burgeoning, as evidenced by many schools in research institutions and universities across the world introducing new modules and courses (e.g., big data analytics, urban simulation models, smart urban metabolism, smart urbanism, and a range of data-driven applications pertaining to mobility, transport, environment, health care, energy, and education) into sustainable urban planning, especially within ecologically and technologically advanced nations (see Bibri and Krogstie 2016a). One of the research issues being under scrutiny and investigation is the challenges of urban big data in terms of how to deal with the complexities, discrepancies, and compatibilities associated with various methodologies, data management and analysis procedures, data sharing and quality, data privacy and security, and data governance. For example, some international research institutions have advocated for a systematic approach to integrate various sources and types of data to support sustainable urban planning and management, including geospatial, temporal, simulated, visual, quantitative, and qualitative (Kharrazi et al. 2016). Another strategic value of investing in research and education in the direction of urban big data lies in training and educating a new generation of interdisciplinary researchers, scholars, and practitioners within the domain of urban sustainability, as well as in gaining new knowledge to explore opportunities of using and applying data in solving real-world problems within smart sustainable cities of the future. Several centers for research and innovation within applied urban science are increasingly providing urban sustainability stakeholders and professionals with a learning channel and platform through offering massive open online courses and programs on big data analytics techniques and practices (e.g., Kharrazi et al. 2016).

5.11 Conclusions

The use of big data analytics in urban planning has great potential to fundamentally change the way smart sustainable cities can function and be managed sustainably, efficiently, and safely with regard to natural resources, infrastructures, facilities, and services and thus improve their environmental, social, and economic performance. We stand at a threshold in beginning to make sense of big data technologies and their associated analytical solutions that will have a seminal influence on how smart sustainable cities as complex, dynamic, and evolving systems can be planned and developed within the next decades. This is heralding a new urban era in which well-informed, strategic, fact-based decisions in sustainable urban planning practice will be based on the analysis of huge amounts of data—data-driven decision-making (DDD)—generated from multiple, diverse sources distributed across many urban domains, involving all urban systems as operating and organizing processes of urban life. The ultimate aim is to effectively monitor, understand, and analyze smart sustainable cities and strategically assess and continuously improve their contribution to the goals of sustainable development. The DDD approach will require access to and utilization of large masses of urban data on the basis of data science principles, processes, and techniques incorporated in cutting-edge technologies deployed and applied by various urban entities involved in different tasks of the planning of smart sustainable cities. By all indicators, the use of big data analytics in urban planning will continue to evolve and grow sophisticated, as new advances in data science will emerge. This offers new prospects for developing and deploying a wide variety of data-centric applications across all the domains of smart sustainable cities as future techno-urban visions. These applications will in turn stimulate new urban planning practices and spur innovations in urban policies. This is underpinned by the recognition that big data analytics will enable smart sustainable cities to leverage their informational landscape as well as effectively integrating it with their physical landscape by amalgamating big data technologies and sustainable urban planning principles to enhance urban operations, functions, services, strategies, and designs in line with the vision of sustainability. To put it differently, the use of big data analytics in planning will be instrumental in realizing the key facets of smart sustainable cities, namely operational functioning efficiency and automation, life quality enhancement, effective utilization of natural resources, and intelligent management of infrastructures and facilities. Indeed, the evolving big data trend is instigating significant ramifications in the domain of sustainable urban planning due to the increasing use of predictive, descriptive, diagnostic, and prescriptive analytics and related models and simulation methods, which have the potential to transform how urbanites interact with each other and their environment (including city infrastructures and facilities) as well as benefit from the ecosystem and human services the city has to offer by means of their deployment in a wide variety of operations, functions, strategies, and services as part of urban systems.

The principle aim of this chapter was to explore the real potential of big data and data-driven decision-making for revolutionizing or transforming the process of planning for the purpose of achieving the goals of sustainable development in the context of smart sustainable cities. There are many uses of big data analytics for decision-making in relation to sustainable urban planning areas, namely research and analysis, sustainable development, strategic thinking, environmental planning, transportation planning, land-use planning, energy management, (socio-)economic forecasting, landscape architecture, urban design, policy recommendations, and public administration. Examples include, and are not limited to, determining the best uses of land and resources, devising ways to redevelop urban areas, monitoring and optimizing transportation and energy systems, managing traffic systems, distributing public services and facilities, designing new communities, and checking and assessing the impacts of urban policies. In light of this, we may reasonably expect that big data will become a strategic source and synergic asset in smart sustainable cities of the future in terms of the knowledge necessary for enhancing the predictive and strategic strands of planning. The value and innovative nature of the useful knowledge extracted from big data in this context lies in catalyzing and boosting the process of sustainable development toward achieving the long-term goals of sustainability through improving physical forms, infrastructures, networks, facilities, services, and administration procedures. This can be accomplished by developing urban intelligence functions and simulation models based on big data analytics for supporting decisions pertaining to optimization, control, management, design, and planning for the purpose of advancing the contribution of smart sustainable cities to the goals of sustainable development. In other words, through the analysis of data detailing urban systems and the underlying processes and activities, it becomes feasible to manage and plan smart sustainable cities by transforming these data into intelligence that can aid in better understanding and dealing with the challenge of urban sustainability on the basis of new patterns, insights, and trends necessary for developing advanced solutions for urban sustainability, which would otherwise be impossible to devise from single source alone.

We argue that the increasing proliferation and variety of urban data due to new and more extensive sources of data and their increasing integration are adding a whole new dimension to urban planning, which is in turn shifting the emphasis from longer term strategic planning to short-term and dynamic thinking about how smart sustainable cities can operate and be managed and developed. In addition, we believe that big data innovations entail how new data-driven transformations are facilitated and applied as well as diffused throughout urban systems, rather than simply denoting a significant growth in volume and variety of urban data. With big data analytics driving decisions in sustainable urban planning, the big data paradigm is in a penetrative path toward safely fueling unhindered progress on many scales, thus paving the way for boosting the process of sustainable urban development toward achieving the required level of sustainability in the context of smart sustainable cities. However, urban big data require huge investments in data infrastructure and involve significant challenges that need to be addressed and overcome in the road to achieve, or before realizing the potential benefits associated with, sustainability through smart planning practices. Moreover, to achieve the benefits being offered by big data technologies in relation to urban planning requires considerable financial and organizational resources, dedicated institutional structures, focused practices, and urban stakeholders' alignment and involvement. Regardless, what is at stake today in the debate over the impact of big data on smart sustainable cities of the future is that the underlying core enabling technologies, namely pervasive sensing, data processing, and networking technologies, are enabling us to rethink some of the core assumptions underlying sustainable urban planning as well as how we value sustainable urban living. As long as big data analytics is motivated by sustainable development agendas and hence not used meaninglessly as to monitoring, understanding, probing, assessing, and planning smart sustainable cities, it will drastically change the way we plan them to improve their contribution to sustainability over the long run. Research endeavors for advancing data science and related big data technologies are imperative and worthy given the rewarding and valued outcomes of their use in the planning of future cities as human settlements.

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Chapter 6
Systems Thinking and Complexity Science and the Relevance of Big Data Analytics, Intelligence Functions, and Simulation Models

Abstract Smart sustainable cities are complex systems par excellence. This is manifested in a variety of ways to think of and define the underlying many subsystems as connected and joined together by a web of relationships that interact to produce collective behavior that cannot easily be explained in terms of interactions between the individual constituent elements. As such, they involve special conundrums, intractable problems, and complex challenges pertaining to sustainability and urbanization. It follows that to deal with such systems requires newfangled ways founded on more innovative solutions and sophisticated methods with respect to how cities can be monitored, understood, managed, planned, and developed. This necessitates leveraging the advance and prevalence of ICT in the transition toward the needed sustainable urban development in an increasingly urbanized and computerized world. Importantly, smart sustainable cities require advanced thinking approaches to be well understood and illuminated so as to enable more effective actions necessary for enhancing their functioning and adaptation in ways that guide their development toward sustainability. The aim of this chapter is twofold. Grounded in systems thinking and complexity science as theoretic approaches, this chapter endeavors to systematically explore the key underlying structures, behavioral patterns, conditions, relationships, and interactions pertaining to smart sustainable cities as complex systems, and to elucidate the related principles in terms of methods, mechanisms, and goals. The intent of offering the knowledge to describe and analyze such systems accordingly is to surface noteworthy relationships as well as their implications for sustainability so as to provoke thought, foster deeper understanding, and create fertile insights, with the primary purpose of making visible possible places for actions that improve the contribution of smart sustainable cities to the goals of sustainable development. This can be accomplished by means of devising powerful urban intelligence functions and robust urban simulation models for strategic decision-making based on big data analytics in conjunction with urban design concepts and planning principles of sustainability. Accordingly, this chapter also discusses the potential of big data analytics and related urban intelligence functions and urban simulation models for, and the role of urban design in, catalyzing and advancing the strategic process of sustainable development by proposing innovative approaches and solutions for

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monitoring, managing, planning, and designing smart sustainable cities of the future. The main argument is that the systems thinking and complexity science are integral to the understanding of smart sustainable cities, which is a moving target in that they are becoming more complex through the very technologies being used to understand them. Moreover, advanced ICT is founded on the application of complexity theory to urban problems in terms of tracking the changing dynamics, disentangling the intractable problems, and tackling the challenges pertaining to urban systems, which are in and of themselves becoming ever more complex. As high-performance computers have become an indispensable source of information, complex systems cannot be understood and studied without the use of computers and big data analytics.

Keywords Smart sustainable cities · Systems thinking · Systems theory
Complexity science · Big data analytics · Urban intelligence functions
Urban simulation models · Intractable problems · Complex systems
Urban sustainability

6.1 Introduction

Smart sustainable cities are complex systems par excellence, and thus involve special conundrums, intractable problems, and complex challenges pertaining to sustainability and urbanization. It follows that to tackle or deal with such systems requires newfangled ways founded on more innovative solutions and sophisticated approaches with respect to how cities can be monitored, understood, analyzed, managed, planned, and developed. This, in turn, must be based on systems thinking and complex systems approach into explaining, understanding, and dealing with smart sustainable cities so as to enable more effective actions necessary for enhancing their functioning and adaptation in ways that guide their development toward sustainability. This compound argument is deductively valid due to its premises providing strong support for its conclusion, or owing to the truth of its premises guaranteeing the truth of its conclusion. It is also a strong argument because all of its premises can be justified, as we will elucidate next.

Smart sustainable cities are inherently intricate and dynamically changing through the very technologies being used to monitor, understand, and analyze the underlying physical structures, spatial and temporal scales, urban services, and urban processes related to management, planning, and development to improve their contribution to sustainability and thus increase their ability to confront urbanization through computationally and analytically advanced decision-support systems. Batty et al. (2012, p. 483) describe smart sustainable cities as complex systems for they are "developed through a multitude of individual and collective decisions from the bottom up to the top down. The complexity sciences are integral to their understanding which is a moving target in that cities themselves are becoming more complex through the very technologies that we are using to understand them." Bibri and Krogstie (2017a, p. 12) describe smart sustainable cities as a social fabric made of a complex set of networks of relations between various synergistic clusters of urban entities that, in taking a holistic or systemic perspective converge on a common approach into using and applying smart technologies to create, develop, disseminate, and mainstream innovative solutions and sophisticated methods that help provide a fertile environment conducive to advancing sustainability by strategically assessing and continuously improving the contribution to the goals of sustainable development. Here, ICT can be directed toward and effectively used for collecting, processing, analyzing, and synthesizing data on every urban domain involving forms, structures, infrastructures, networks, facilities, services, and citizens, which can then be employed to develop urban intelligence functions and build urban simulation models to gain predictive insights for strategic decision-making associated with sustainability. Another conceptualization of the term provided by Bibri and Krogstie (2016, p. 11) states: "as a dynamic, complex interplay between scientific innovation, technological innovation, environmental innovation, urban design and planning innovation, institutional innovation, and policy innovation, smart sustainable cities represent and involve inherently complex socio-technical systems of all sorts of innovation systems. Such systems, which focus on the creation, diffusion, and utilization of knowledge and technology, are of various types (variants of innovation models), including national, regional, sectoral, technological, and Triple Helix of university–industry–government relations."

As such, smart sustainable cities involve wicked problems and timeless challenges pertaining to sustainability and urbanization, which are to be disentangled and solved, respectively, with the support of advanced ICT. Indeed, the concept of smart sustainable cities has emerged as a result of three important global trends at play across the world, namely the diffusion of sustainability, the spread of urbanization, and the rise of ICT (Bibri and Krogstie 2016, 2017a, b). The idea is to leverage the advance and prevalence of ICT in the transition toward the needed sustainable development in an increasingly urbanized and computerized world. The rapid urbanization of the world implies significant challenges for city governments associated with environmental, economic, and social sustainability due to the issues engendered by urban growth in terms of intensive energy consumption, endemic congestion, saturated transport networks, air and water pollution, toxic waste disposal, resource depletion, inadequate decision-making and planning systems, inefficient management of urban infrastructures and facilities, poor housing and working conditions, social inequality and vulnerability, and so on (Bibri and Krogstie 2017a). These add to the problems related to the unsustainability of the form of the contemporary city. Specifically, the existing built environment is associated with numerous environmental, economic, and social impacts, including unsustainable energy use and concomitant greenhouse gas (GHG) emissions, increased air and water pollution, environmental degradation, land use haphazard, outdated (nonautomated, non-digital) infrastructures, inappropriate urban design and related social deprivation and community disruption, ineffective mobility and accessibility, increased transport needs and traffic congestion, and public safety and health decrease, but to name a few (Bibri and Krogstie 2017a). All these intractable problems put urban systems under increasing pressure due to the challenges of sustainability and urbanization. To rise to these substantial challenges, ICT innovations can provide integrated information intelligence for enhancing urban operational functioning, management, planning, design, socioeconomic forecasting, and policy development on the basis of participatory, polycentric, and digital models and processes of governance. Accordingly, smart sustainable cities are to be supported by a pervasive presence and massive use of advanced ICT, which, in connection with various urban systems and domains and how these intricately interrelate and are coordinated, enables them to control available resources safely, sustainably, and efficiently to improve economic and societal outcomes.

In all, smart sustainable cities as complex systems require advanced thinking approaches to be well understood and illuminated so as to enable more effective actions necessary for enhancing their functioning and adaptation in ways that guide their development toward sustainability. In line with this argument, Meadows and Wright (2012) state that "as our world continues to change rapidly and become more complex, systems thinking will help us manage, adapt, and see the wide range of choices we have before us. It is a way of thinking that gives us the freedom to identify root causes of problems and see new opportunities." Especially, some of our solutions have created further problems, and many complex problems have been solved by focusing on external factors because they are embedded in larger systems. As real messes, the problems rooted in the internal structure of complex systems as well as their interaction with their environment (e.g., pollution, environmental degradation, toxic waste, economic instability, social inequality, unemployment, and chronic disease) have been difficult to deal with and refused to go away. They persist despite the analytical ability, technical intelligence, and human brilliance that have been directed toward circumventing and eradicating them. They persist because they constitute intrinsically systems problems—undesirable patterns of behavior characteristic of the system structures and reciprocal relationships resulting from the profound interactions that produce those patterns. They will yield only as we reclaim our holistic thinking as well as intuition and thereby see the whole system as the source of its own problems, and find the astuteness and wisdom to restructure it and reshape its interaction in ways that control or predict the cycling of reciprocal relationships to yield positive patterns of behavior.

Set against the preceding background and grounded in systems thinking and complexity science as theoretic approaches, this chapter endeavors to systematically explore the key underlying structures, behavioral patterns, conditions, relationships, and interactions pertaining to smart sustainable cities as complex systems, and to elucidate the related principles in terms of methods, mechanisms, and goals. The intent of offering the knowledge to describe and analyze such systems accordingly is to surface noteworthy relationships as well as their implications for sustainability so as to provoke thought, foster deeper understanding, and create fertile insights, with the primary purpose of making visible possible places for actions that improve the contribution of smart sustainable cities to the goals of sustainable development toward achieving sustainability. This can be accomplished by means of devising powerful urban intelligence functions and robust urban simulation models for strategic decision-making based on big data analytics, coupled with urban design concepts and planning principles of sustainability. Accordingly, this chapter also discusses the potential of big data analytics and related urban intelligence functions and urban simulation models for, and the role of urban design in, catalyzing and advancing the strategic process of sustainable development by proposing more innovative approaches and solutions for monitoring, managing, planning, and designing smart sustainable cities of the future.

This chapter is structured as follows. Section 6.2 introduces and discusses the theoretical frameworks adopted by the study. Section 6.3 addresses sustainability, four sustainability principles, and sustainability science from a systems thinking view. In Sect. 6.4, we describe and discuss smart sustainable cities as complex systems. Section 6.5 looks at urban sustainability through the lens of systems thinking. Section 6.6 unveils some structural issues of smart sustainable cities with respect to the ICT Infrastructure as a technological component. Section 6.7 provides an analytical account of deep urban and environmental sustainability. In Sect. 6.8, we identify and discuss five concepts of systems thinking in relevance to smart sustainable cities. Section 6.9 covers different facets of complexity science in relation to smart sustainable cities: complex systems simulation in terms of challenges and driving forces, new prospects and opportunities of complexity science, and a new class of urban simulation models and related challenges. In Sect. 6.10, we highlight and discuss the role of big data analytics in disentangling the intractable problems pertaining to smart sustainable cities with regard to sustainability and urbanization. Section 6.11 elucidates the relevance and prominence of intelligence functions and simulation models as sophisticated approaches as to tackling the complex problems associated with urban sustainability. In Sect. 6.12, we throw some light on urban design perspectives in light of systems thinking. This chapter ends, in Sect. 6.13, with key concluding remarks along with some thoughts.

6.2 Theoretical Frameworks

6.2.1 Systems Thinking

Systems thinking is the broad paradigm of thinking. It revolves around seeing the big picture of phenomena; viewing systems from a broad and holistic perspective (structures, behavioral patterns, interactions, relationships, influences, dynamics, cycles, etc.), rather than based on specific events and visible interacting variables. Conceptions in contemporary science are concerned with what is termed wholeness, i.e., problems of organization, phenomena not resolvable into local events, dynamic interactions manifest in difference of behavior of parts when isolated or not understandable by investigation of their respective parts in isolation (von Bertalanffy 1968a). In many fields of endeavor, the necessity of systems thinking is emphasized, and there can be little doubt that the systems approach marks a necessary, consequential, and genuine development in science and world-view (László 1972).

There are multiple definitions of systems thinking, which essentially mean the same thing. The common thread running through all the definitions is the concept of holistic thinking in the sense of considering all the aspects of the system (characteristics, structures, behavioral patterns, relationships, interactions, dynamics, cause–effect, etc.) or the entirety of the object of interest and the mutual interactions with others when thinking about or studying complex phenomena. This results to a better understanding of why things are the way they are, and how to develop solutions or design interventions, which are highly likely to succeed and to enhance the conditions under consideration. As supported by Senge (1990, p. 69), "systems thinking is a discipline for seeing the 'structures' that underlie complex situations, and for discerning high from low leverage change. That is, by seeing wholes we learn how to foster health. To do so, systems thinking offers a language that begins by restructuring how we think." To add, systems thinking enables to solve problems so they stay solved, and crucially, to not create new problems in the process we have to deal with later. This is at the core of urban sustainability and hence the notion of smart sustainable cities. Accordingly, it is of critical importance to look at the whole rather than the parts of such cities when dealing with sustainability and urbanization as complex issues to create a better understanding of what is happening, to enable more effective actions for improvement, and to provide a framework for designing the best means for implementation. In all, systems thinking focuses on systems, subsystems, patterns of behaviors, and system interrelationships in a complex situation. It is a set of general principles spanning diverse fields, including physics, social sciences, engineering, and management, representing a framework for seeing behavioral patterns rather than static snapshots and interrelationships rather than things (Senge 1990).

Systems thinking has extensively been applied to, and greatly influenced, human endeavors to understand and change organizations of different scales, structures, and complexities. Unlike traditional forms of analysis that focus on fragmenting and separating the individual parts of what is being studied, system's thinking focuses on how to understand the system from studying the behavior of the whole and not the parts the system is composed of, to reiterate. Science tried in the past to explain observable phenomena and problems of organization by reducing them to an interplay of elementary units investigable independently of each other (von Bertalanffy 1968a). Instead of isolating the components of the system being studied, systems thinking focuses moreover on the dynamic interaction of the whole with its environment. This approach has proven to be exceedingly effective in solving difficult problems involving complexity issues. Indeed, by considering the whole as well as the parts and their mutual interactions, the systems view minimizes the risk of potentially losing the most relevant emergent characteristics of the system being studied, and develops a deeper level of understanding. Figure 6.1 represents a positioning of systems thinking, where each stage in the continuum provides a strengthening of the systems view. The explicit description of our thinking provided

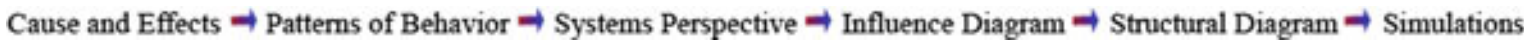

Fig. 6.1 Systems thinking continuum. Adapted from: Richmond (1991)

by each level of understanding enables to reduce potential ambiguity and misunderstanding in our communication pertaining to how we think or conceive of complex systems.

Cause and Effect is about identifying the cause and act, and represents thoughts where actions are primarily reactionary.
Patterns of Behavior entail recognizing the way things have changed over time and taking this into account before taking action.
Systems Perspective consists of looking at, by standing back far enough in space and time to be able to see, the underlying web of ongoing, reciprocal relationships which are cycling to generate the patterns of behavior that complex system are exhibiting.
Influence Diagram is a kind of simple map of the reciprocal relationships thought to be principally responsible for generating the patterns of behavior that complex systems are exhibiting.
Structural Diagram represents a more disciplined map showing what really makes complex systems tick, a process during which the mechanisms believed that such systems are using to control themselves can be laid out.
Simulations translate the structural diagram into a set of equations characterizing the nature of the relationships laid out in the structural diagram, as well as their direction and strength. Then comes the simulation of the system behavior on a computer. The key question to answer here is whether the set of reciprocal relationships pieced together do generate the patterns of behavior that are being generated by the system.

6.2.2 Systems Theory

Systems theory is the science in terms of laws, principles, and theorems. Systems science is "the ordered arrangement of knowledge acquired from the study of systems in the observable world, together with the application of this knowledge to the design of man-made systems." (M'Pherson 1974, p. 6, cited in Hieronymi 2013). For example, designing sustainable technologies should be grounded in efficiency, regeneration, resiliency, and sufficiency, as well as mimic natural patterns, processes, and rhythms. Further, systems theory can be viewed as a key regulative device in science in terms of eschewing ungrounded assumptions in science and hence their detrimental effects on practice. As a major scientific discovery and systematic approach to thinking, systems theory aims at surfacing noteworthy behavioral patterns and relationships as well as their implications pertaining to complex systems so as to provoke thought and discussion, foster deeper understanding, and create fertile insights, with the purpose of enabling more effective actions for improvement in terms of the functioning, adaptation, growth, and evolution of such systems toward a desired state. Concerned with the interdisciplinary study of systems, systems theory brings together laws, principles, and concepts from a number of disciplines, including computer science, physics, philosophy of science, biology, engineering, organizational theory and management, ecology, and sociology, among others. In short, it is a domain of a transdisciplinary and interdisciplinary character, and as such, it serves as a bridge for dialogue within the field of systems science as well as between autonomous fields of study. To note, the social sciences were of particular importance to the establishment of systems theory since its inception. Systems theory emerged as an alternative approach to scientific thinking, and attempted to revive the unity of science. Thus, it is about broadly applicable concepts and principles, as opposed to those applicable to one discipline or field of knowledge. Its primary goal is to systematically discover the structures, patterns, conditions, dynamics, relationships, interactions, and constraints of complex systems, and to illuminate the related principles (methods, mechanisms, tools, designs, etc.) that can be discerned and applied at every level of nesting pertaining to such systems, as well as to every field for achieving optimized equifinality. Accordingly, it focuses on the arrangement (structure) of, and the relations (interaction) between, the components that connect them to a whole that determines a system, which is independent of the concrete substance of the individual elements and cannot be reduced to the properties of its components. von Bertalanffy (1962) points out that real systems are open to, and interact with, their environments, which allows them to acquire qualitatively new properties through emergence, resulting in continual evolution. Also, a system is an entity which maintains its existence through the mutual interaction of its parts (Davidson 1983). In systems theory, emergence as a phenomenon and central in theories of complex systems entails larger entities arising through interactions among smaller entities such that the former exhibits properties that the latter does not. Almost all accounts of emergentism involve a form of ontological or epistemic irreducibility to the lower level (O'Connor and Wong 2012).

As far as concerns general system theory, it involves models, laws, formulation, and derivation of universal principles that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relation between them (von Bertalanffy 1968a). It "should be an important regulative device in science," to guard against superficial analogies that "are useless in science and harmful in their practical consequences" (von Bertalanffy 1950a, p. 142).

6.2.3 Complexity Science and Complex Systems

As an emerging approach to research and a multidisciplinary subject, complexity science is the scientific study of complex systems, systems composed of many parts connected and joined together by a web of relationships that interact to generate collective behaviors that cannot easily be explained on the basis of the interaction between the individual constituent elements. Accordingly, complexity entails the way a vast number of complicated and dynamic sets of relationships, interactions, or dependencies can produce some behavioral patterns. Complexity science is a set of conceptual tools and theories from an array of disciplines (Benham-Hutchins and Clancy 2010; Paley and Gail 2011). It deals with complex systems as a collection of interconnected parts and relationships that are dynamical, unpredictable, and multidimensional in nature. It has been taken up in both natural and social sciences. In a wide range of complex systems that are on focus within these sciences, computational modeling, as based on mathematical developments and modeling approaches from physics, is undertaken to study the behavior of such systems to better understand them. Software engineering expertise can be used to apply new results as well as to inspire new approaches (Batty et al. 2012). Complex systems are characterized by nonlinearity and thus require more than simplistic linear thinking, as they feature a large number of interacting elements (patterns, agents, processes, etc.) whose aggregate activity (behaviors, relationships, interactions, etc.) does not emanate from the summations of the activity pertaining to the individual elements. As such, they typically exhibit hierarchical self-organization under some kind of selective pressures. Examples of complex systems are cities, ecosystems, organisms, global climate, neural network, human brain, ICT network, and ultimately the entire universe. As an approach to science, complex systems investigates how the dependencies, relationships, or interactions between the system's parts give rise to its collective behaviors and how the system interacts and forms relationships with its environment (Bar-Yam 2002). So, it is chiefly concerned with the behaviors and properties of systems. As a research approach, it involves problems in many diverse disciplines, including information theory, computer science, mathematics, statistical physics, biology, ecology, nonlinear dynamics, sociology, and economy. As an interdisciplinary domain, it draws on theoretical contributions and perspectives from these disciplines, e.g., spontaneous order from the social sciences, chaos from mathematics, cybernetics from technology, self-organization from physics, adaptation from biology, and many others.

The concerns that complexity science addresses have grown out of investigations from a varied intellectual ancestry, including cybernetics, general systems theory, chaos theory in dynamical systems, complex systems, mathematical systems, and complex adaptive systems (social systems, technological systems, urban systems, etc.) where the parts actively change the way they interact. The increased use of computer simulation created research in the simulation of adaptive behavior in the 1990s. From 2000s and onward complexity science takes stock of what has been accumulated as substantive knowledge of all this rich background of work. A key part of the current emphasis of complexity science is its application to practical technological and engineering systems in that control systems need to be designed, managed, and constructed as they proliferate and increase in size and connectivity in a variety of contexts, e.g., smart sustainable cities. It is desirable to have the ability to build systems that are scalable, robust, and adaptive by using such properties as self-organization, self-adaptation, self-regulation, self-repair, and evolution as a way of mimicking biological systems. Complexity science is a subject of study that is well positioned to bringing together deep scientific questions pertaining to sustainability and urbanization with application-driven goals across the field of smart sustainable cities. Its contemporary applications are complemented by a rich background of theoretic work.

Complexity science touches on all facets of technology and science, creating lots of new opportunities and horizons in research. Important to underscore is that complexity is not just determined by the large number of parts of a system with very intricate design, but rather by such dynamical properties as self-organization, spontaneous order, adaptation, emergence, feedback loops, and nonlinearity, among others. In the context of smart sustainable cities, technological and engineering systems based on big data analytics and context-aware computing are primarily designed to minimize these tricky dynamical properties. These can make smart sustainable cities as systems difficult to design, predict, and control. However, if desirable emergent behaviors and processes can be managed, harnessed, and exploited, they can allow to move beyond the limits of conventional technological and engineering systems that are merely complicated. Apart from that, we are dealing with the traditional approach to tackling complexity, which aims to reduce or constrain it and thereby typically involves compartmentalization: dividing a large system into separate parts. Technological and engineering systems are susceptible to failure for they are often designed using modular components, and where failure stems from the potential issues arising to bridge the divisions.

6.2.4 Some Relevant Links Between Theoretical Frameworks

Dynamical properties such as feedback loops, adaptation, nonlinearity, and emergence as specific concepts important to complex systems originate in systems theory. Complex systems is indeed a subset of systems theory. Accordingly, both complex systems and general systems theory focuses on the collective or system-wide properties and behaviors of interacting entities. But the latter is concerned with a much broader class of systems, including linear systems where effect is directly proportional to cause, or noncomplex systems where reductionism may hold viable. Indeed, as mentioned above, systems theory entails the ordered arrangement of knowledge accumulated from the study of all classes of systems in the observable world. As such, it seeks to describe, explain, and explore all categories of systems, and one of its objectives is the invention of classes that are of value to researchers across a wide variety of fields. Given the link between systems theory and complex systems, the former provides two key contributions to the latter: (1) an interdisciplinary perspective in that shared properties linking systems across disciplines justify the quest for modeling approaches applicable to complex systems across those disciplines, and (2) an emphasis on the way in which a system's components interact and depend one on another can determine system-wide properties that produce collective behaviors.

6.3 Sustainability, Sustainability Principles, and Sustainability Science as Grounded in Systems Thinking

The notion of sustainability was born from the realization that the predominant paradigm of social, economic, and urban development was oblivious to both the risks of environmental crises as well as to the implications of social decays, causing ecological and social deprivation and imperiling future life. In other words, sustainability has grown out of an urgent need for real, radical change—due to serious concerns that the model of societal development has been performing poorly in protecting the environment and improving the quality of people's lives. In particular, there is mounting evidence that economic development has caused ecological deprivation and unprecedented levels of GHG emissions. This is due to the instrumental rationality underlying the economic model. This specific form of rationality, the dominant mode of thinking and action in the industrial world, focuses on the most efficient means to achieve a specific end, or on identifying problems and working directly—and often unreflectingly—towards developing immediate solutions, thereby lacking any consideration of limits and overlooking the consequences of particular choices and decisions. Further, the obliviousness to the environmental threats fueled by the instrumental rationality of the economic model has triggered innumerable complex environmental crises with catastrophic global effects on human health, well-being, stability, and safety. Predictably, it has been argued that it is only by altering the foundational theories and assumptions underlying economics and politics that sustainable development may come true, and eventually sustainability may be achieved (Bibri 2015). In fact, there is a need for the kind of rationality that goes beyond thinking instrumentally to embrace ways of seeing things from a more sensible, reflective, and holistic perspective.

Grounded in a holistic thinking perspective, sustainability is based on the idea of consciously and incessantly going with the grain of nature and providing the conditions for deploying the frameworks necessary for its operationalization and its translation into practices in a more dynamically innovative way in order to reach a sustainable society. As such, it has widely been adopted to primarily guide and configure societal development (social system functioning, adaptation, growth, and evolution) in its prominent spheres, including science and innovation, technology, economy, urban development, policy, politics, ethics, institutionalization, and culture. The underlying premise is that it is grounded in an all-embracing understanding of the complex challenges and mounting problems facing society, which is necessary for making all-inclusive decisions and taking well-informed actions for its long-term benefit.

Accordingly, sustainability as a form of holistic thinking grounded in systems view deals with wholes rather than parts. One way of thinking about this is in terms of a hierarchy of levels of socio-ecological organization and of the different emergent properties that are evident in the whole biosphere that are not evident at the level of economic and political systems as taken as separate units of analysis. Sustainability is a state in which society does not systematically undermine natural and social systems within the biosphere, i.e., a state in which the four "sustainability principles" are not violated (Robèrt et al. 1997). In more detail, in such state the natural system is not subject to resource depletion and intensive consumption, hazardous substances, environmental degradation, and concomitant environmental risks, and, as of equal importance, the social system does not render people subject to conditions that inhibit their ability to satisfy their needs and aspirations. Undermining natural and social systems can occur through pollution, environmental degradation/ecological deprivation, health decrease, social instability, social injustice, and social hazard. Accordingly, sustainability starts by looking at the nature and behavior of the whole system (socio-ecological organization) that those participating have agreed to be worthy of study. This involves the three following criteria, according to Pearson and Ison (1997):

- Taking multiple partial views of "reality",
- Placing conceptual boundaries around the whole, and
- Devising ways of representing the whole or systems of interest.

The four sustainability principles, which are considered as basic principles for socio-ecological sustainability as developed through scientific consensus, are derivative from basic laws of science, including laws of thermodynamics, cycles of nature, conservation of matter, and so on, and have been peer-reviewed by the international scientific community (e.g., Holmberg and Robèrt 2000). In the sustainable society, according to Holmberg and Robèrt (2000), nature is not subject to systematically increasing

1. concentrations of substances extracted from the Earth's crust;
2. concentrations of substances produced by society;
3. degradation by physical means, and in that society; and
4. people are not subject to conditions that systematically undermine their ability to meet their needs.

The purpose of articulating sustainability with scientific rigor is to make it more intelligible, more useful, and clearer for measuring, analyzing, and managing human activities within society. A significant contribution in this line was the development of the above listed four guiding sustainability principles to provide a principle-level definition of sustainability. The sustainability principles should be, according to Holmberg and Robèrt (2000, p. 298):

- Based on a scientifically agreed upon view of the world;
- Necessary to achieve sustainability;
- Sufficient to achieve sustainability;

- General to structure all societal activities relevant to sustainability;
- Concrete to guide action and serve as directional aides in problem analysis; and
- Nonoverlapping or mutually exclusive in order to enable comprehension and structured analysis of the issues.

This scientific explanation of sustainability clarifies how to avoid the destruction of the biosphere (Holmberg and Robèrt 2000; Ny et al. 2006; Robèrt et al. 2002). Scientific principles are the foundation of our understanding of the biosphere and how it operates. By means of understanding the laws of thermodynamics, the cycles of nature, and the conservation of matter, scientists have come to concur that

- Natural processes disperse matter and energy;
- Neither matter nor energy disappears;
- The value of materials exists in their concentration, structure, and purity;
- Photosynthesis is the primary producer in the biosphere; and
- Humans are a social species.

Sustainability has theoretical foundations from which it has grown that have begun to solidify into a defined science (Lee 2000). As a flourishing academic discipline, sustainability science has emerged in the early 2000s (e.g., Kates et al. 2001; Clark 2007; Clark and Dickson 2003). Sustainability science is concerned with "advancing knowledge on how the natural and human systems interact in terms of the underlying (changing) dynamics, with the purpose of designing, developing, implementing, evaluating, and perennially enhancing engineered systems as practical solutions and interventions that support the idea of the socio-ecological system in balance, as well as nurturing and sustaining linkages between scientific research and technological innovation and policy and public administration processes in relevance to sustainability."(Bibri and Krogstie 2017a, p. 6). Sustainability science is defined by Kieffer et al. (2003, p. 432) as "the cultivation, integration, and application of knowledge about Earth systems gained especially from the holistic and historical sciences…coordinated with knowledge about human interrelationships gained from the social sciences and humanities, in order to evaluate, mitigate, and minimize the consequences…of human impacts on planetary systems and on societies across the globe and into the future." As an interdisciplinary field, it brings together disciplines across the natural sciences, social sciences, and applied and engineering sciences. As a research field, it seeks to give the "broad-based and crossover approach" of sustainability a solid scientific foundation (Bibri and Krogstie 2017a). It also provides a critical and analytical framework for sustainability (Komiyama and Takeuchi 2006), and "must encompass different magnitudes of scales (of time, space, and function), multiple balances (dynamics), multiple actors (interests), and multiple failures (systemic faults)" (Reitan 2005, p. 77). In all, sustainability science is at the core of systems science.

To grasp the integrated whole of the socio-ecological system in terms of the complex social and multidimensional environmental characteristics, behavioral patterns, relationships, interactions, and dynamics to solve the underlying problems necessitates globally integrated political consensus and collaboration between institutional, social, economic, scientific, and technological disciplines, as well as the active engagement of citizens, communities, organizations, and institutions. One key mission of sustainability science as a more disciplined framework is to aid in coordinating cross-disciplinary integration necessary as a critical step toward a global joint effort and concerted action (Bibri and Krogstie 2017a). In addition, the way in which sustainability science as a scholarly community can best contribute to the understanding and implementation of the goals of sustainable development should be based on an in-depth critical analysis and evaluation through scenario analysis, scientific research, technological innovation, stakeholder relationships, participatory decision-making, and policy recommendations and impacts. In a nutshell, to achieve these goals requires taking an all-inclusive approach by mobilizing diverse actors, factors, and resources.

6.4 Smart Sustainable Cities as Complex Systems

The system concept has gained central importance in contemporary society. Smart sustainable cities are complex systems par excellence. This is manifested in a variety of ways to think of and describe the underlying subsystems (urban systems) as a whole using such concepts as boundaries, homeostasis, adaptation, reciprocal transactions, feedback loops, dynamics, mesosystem, and chronosystem. Indeed, as complex systems, smart sustainable cities are characterized by the following:

- More than the sum of their parts (subsystems) that are related directly or indirectly;
- Organized entities made up of interrelated and interdependent parts;
- Encapsulated and defined by their boundaries, thereby being distinguished from other systems in the environment;
- Nested inside (i.e., their components may themselves be complex systems) and overlap with other systems in the environment;
- Bounded in time and space yet may be intermittently operational and their parts are not necessarily co-located;
- Comprising processes that transform inputs into outputs;
- Are open systems in the sense that they exist in a thermodynamic gradient and dissipate energy;
- Receiving input from and sending output into the wider environment;
- Autonomous in fulfilling their purpose through internal functions;
- Change in one of their part affects other parts and the whole system;
- Have unpredictable patterns of behavior and relationships with their implications;
- Their positive adaptation and evolution depend upon how well they are adjusted with their environment;
- Have tendency to resist change and maintain status quo;
- Have tendency to make the changes needed to grow to accomplish their goals;

- Engage in circular interactions such that they influence, and are influenced by, other systems;
- Self-correct themselves based on reactions from other systems in the environment;
- Have nonlinear relationships in that a small perturbation may cause a proportional effect or a large effect;
- Have nonlinear behavior over time based on feedback loops, time delays, flows, and stocks;
- Characterized by relationships containing feedback loops (negative and positive feedback). The effects of their parts' behavior are fed back to in such a way that the parts themselves are altered;
- Are adaptive by having the capacity to change and learn from experience; and
- Composed of significant life events that can affect their adaptation in the environment.

There are other features of complex systems that apply to smart sustainable cities, most notably cascading failures, memory, network of complexity, and emergent phenomena. In more detail, a failure in one or more components of such cities can lead to cascading failures because of the strong coupling between components (e.g., energy system and economic system), which may have catastrophic consequences (e.g., environmental crisis) on the functioning of the system (see Buldyrev et al. 2010). Regarding memory, the importance of the history of smart sustainable cities lies in that they as dynamical systems change over time, and prior states may have an impact or influence on present states. More formally, they are most likely to exhibit spontaneous failures and recovery as well as hysteresis (see Majdandzic et al. 2013). To draw on Majdandzic et al. (2016), as a set of interacting systems, smart sustainable cities are likely to have complex hysteresis of many transitions. As regards to the dynamic network of multiplicity, the dynamic network of such cities is of import as a topology. Scale-free networks (Barabasi 2002; Cohen and Havlin 2010; Newman 2010) have many local interactions or relationships and a smaller number of interconnections are often employed. Concerning the potential generation of emergent phenomena, smart sustainable cities exhibit behaviors and processes that are emergent. This implies that hey may have properties that can only be analyzed at a higher level, despite the results being sufficiently determined by the activity of urban systems' basic constituents. For example, smart sustainable cities entail physical, spatial, social, economic, political, and technological development that are at one level of analysis, but their environmental behavior is a property that emerges from the collection of urban systems and needs to be analyzed at a different level.

All the above listed core characteristics of complex systems pertain to smart sustainable cities as a set of interrelated subsystems and related functions, which enable the underlying processes to operate, organize, and direct urban life. Such subsystems and functions include the following:

- Built form (buildings, streets, residential and commercial areas, schools, parks, etc.) involving monitoring, design, evaluation, simulation, and forecast;

- Urban infrastructure (transportation, water supply, communication systems, distribution networks, etc.) involving control, management, optimization, and automation;
- Ecosystem services (energy, raw material, water, air, food, etc.) involving provision, distribution, and efficiency;
- Human services (public services, social services, cultural facilities, etc.) involving delivery, accessibility, and optimization; and
- Administration (mechanisms for adherence to established regulatory frameworks, practice dissemination, policy recommendations, governance models, technical and assessment studies, etc.) involving design, analysis, implementation, evaluation, improvement, and integration.

There are several conspicuous aspects that are of applicability to smart sustainable cities as complex systems. In this respect, the main goal such cities seek to fulfill is to strategically improve and sustain their contribution to the environmental, social, and economic goals of sustainable development through their functioning, adaptation, and growth as part of the process of achieving sustainability as a desired state in their evolution. Also, such cities represent more than the sum of their subsystems (i.e., the operating and organizing processes of urban life supported by advanced ICT) that are involved in the directing of their collective behavior to the state of sustainability due to the other nested interrelationships and interdependencies underlying their subsystems, as well as to the mutual interaction of the whole city system with other systems. Indeed, they involve profound interactions between social, engineered, and environmental systems, and as such, they receive input from and send output into the wider natural system where they are embedded. In doing so, they can cause systematic degradation and concomitant perils to natural environment and human well-being. Additionally, as they are encapsulated and defined by their boundaries as urban forms, they are affected by, and also nested inside, the natural system.

Hence, smart sustainable cities should work toward enhancing the underlying physical, technological, economic, environmental, social, and political systems over the long run by means of sustainable interventions and programs pertaining to their functioning, adaptation, growth, and evolution, thereby maintaining predictable patterns of behavior and stable reciprocal relationships principally responsible for generating such patterns being exhibited. In particular, as their positive adaptation depends upon how well they are adjusted with the environment, they need to make changes to protect themselves and grow to accomplish their goals in terms of achieving the ultimate state of sustainability. One way of doing this is to self-correct themselves based on reactions from the natural system associated with climate change, which relates to the adaptive nature of complex systems in that they have the capacity to change and learn from experience. Failure to combat climate change could cause possibly irreversible disruption, a significant life event that can affect their adaptation. In all, systems thinking enables to better understand smart sustainable cities as complex systems, and thus to have control over their functioning, adaptation, growth, and evolution in line with the vision of sustainability. It enables to create methods and design interventions for dealing with sustainability problems that are highly likely to produce the desired outcomes while minimizing unexpected consequences.

6.5 Urban Sustainability: A Systems Thinking View

As complex systems, smart sustainable cities represent a configuration of parts connected and joined together by a web of relationships, or a family of relationships among the parts behaving as a whole. Underlying the systems thinking view is the idea that smart sustainable cities entail common properties, patterns, behaviors, relationships, interactions, and dynamics that can be identified, analyzed, and used to develop greater insight into the way smart sustainable cities function as a complex phenomenon, with the aim of devising strategies and enabling actions that shape their functioning toward improving their goals to sustainability. Smart sustainable cities are a manifestation of urban sustainability in the sense that they constitute objects that clearly embody or show the theory or abstract idea of urban sustainability.

The systems thinking approach was applied to urban sustainability since its inception, as well as to its related fields, such as systems ecology and systems engineering (e.g., sustainable development). These can be seen as an application of general systems theory to ecology and engineering. Urban sustainability as an interdisciplinary study field focuses on the mechanisms and behavioral patterns involved in the profound interactions between social, environmental, and engineered systems pertaining to cities to understand the underlying reciprocal relationships and changing dynamics, and to contribute to developing (rather upstream) solutions for tackling the complex challenges associated with the systematic degradation of such systems and the concomitant perils to natural environment and human well-being. Hence, it uses holism instead of reductionism, an approach which explains systems in terms of their constituent elements and the individual interactions between them. Accordingly, thinking systemically is about considering smart sustainable cities in their totality along with their characteristics as well as their interaction with their environment, in addition to considering their subsystems along with the interaction between them. In the realm of smart sustainable cities, sustainability involves how these interactions affect the associated challenge as to substantially preserving the urban ecosystem by tackling the continuing decline in resources and lessening pollution and waste levels, while improving the quality of urban life by providing clean air and water and human environment that maintains public health and safety. As a scientific field, drawing on Clark (2007, p. 1737), urban sustainability can be viewed as “a field defined by the problems it addresses rather than by the disciplines it employs; it serves the need for advancing both knowledge and action by creating a dynamic bridge between the two.” Seen from this perspective, it consists of four dimensions: physical, environmental, economic, and social, which should be enhanced in terms of goals and be in balance in terms of concerns over the long run—with support of advanced ICT—to achieve sustainability. This can occur through the strategic process of sustainable urban development that—in seeking to foster and promote sustainable built form, environmental integration, economic development, and social equity as interrelated goals—relies on innovative solutions and novel approaches by unlocking the untapped potential for sustainable transformation that ICT embodies in its disruptive and morphing power as an enabling, integrative, and constitutive technology.

Urban sustainability can be seen as an amalgam of fields to which general systems theory is applied, such as systems ecology and systems engineering as subsets of systems science, which take a holistic approach to the study of ecological and engineering systems, respectively. Following general system theory, urban sustainability focuses on interactions and transactions within and between physical, technological, environmental, ecological, economic, social, and political systems, and is especially concerned with the way the functioning of such systems can be influenced by human interventions and activities. As part of urban sustainability as grounded in general systems theory, systems sustainable development engineering as an interdisciplinary approach and means for enabling the realization and deployment of systems as a set of environmental and ecological technologies. It can be viewed as the application of a systems approach to engineering efforts, as well as the application of engineering techniques to the engineering of systems supportive of environmental and ecological sustainability (see Thomé 1993). In forming a structured development process of solutions that proceeds from concept to design to production, operation, and disposal, systems sustainable development engineering integrates several disciplines and specialty groups into a collective effort. In considering both the urban and the technical needs of all stakeholders, it aims to provide artifacts and processes that meet the needs of these stakeholders. It is at the core of the planning and development of smart sustainable cities, and entails both applied and design sciences related to ICT and industrial systems. As far as systems ecology is concerned, it is an interdisciplinary field of ecology that takes a holistic approach to the study of ecological systems, especially ecosystems (Shugart and O'Neill 1979; Van Dyne 1966; Wilkinson 2006), and central to its approach is the idea that an ecosystem is a complex system exhibiting emergent properties. As a subset of Earth system science, systems ecology is concerned with transactions and interactions within and between biological and ecological systems, and focuses typically on the way the functioning of ecosystems relate to anthropogenic (human-induced) influences. It adopts and extends concepts from the cycles of nature and thermodynamics. These are at the heart of the aforementioned four sustainability principles. The same goes for several other fields that constitute part of urban sustainability as a transdisciplinary, interdisciplinary, and multi-perspectival domain, and to which general systems theory is applied.

In all, urban sustainability is one of the major applications of systems thinking, as it is grounded in an all-embracing understanding of the problems facing cities as complex systems, which is necessary for making all-inclusive, astute decisions and taking well-informed actions for ensuring the long-term benefit and health of cities. In particular, the application of systems thinking to urban sustainability has primarily served to explain the phenomenon of climate change engendered by the domination of the city due to the rapid urbanization of the world's population and the associated multidimensional effects on the environment. This phenomenon pertains to the accumulation or substantial rise of GHG emissions in the atmosphere—the main culprit of global warming—caused principally by activities performed in cities. The reciprocal relationships triggered by the profound interactions between physical, economic, environmental, and social systems pertaining to cities have cycled to generate the patterns of behavior that natural systems are exhibiting, showing dramatic changes over time. They are claimed to be principally responsible for generating these patterns of behavior due principally to the intensity of economic activities and the associated energy consumption and concomitant environmental risks, pushed by the institutional and political structures that are oblivious to environmental crises. Indeed, cities are the engines of economic growth and thus major consumers of energy resources and significant contributors to GHG emissions. Evidence shows that the anthropogenic factor is behind disturbance to natural systems, which accelerates climate change (IPCC 2007). And failure to combat climate change may cause possibly irreversible disruption. To address this looming issue, smart sustainable cities have emerged as a holistic approach to urban development to respond to the challenge of environmental sustainability. They are becoming unavoidable as sustainability transitions within technologically and ecologically advanced nations (Bibri and Krogstie 2016). This relates to the purpose of thinking systemically in terms of developing strategic interventions as a result of gaining greater insight into the way natural systems function in interaction with human systems in order to preclude the atmospheric levels of GHG emissions from exceeding the so-called "safe" threshold. In this regard, exploring the possible convergences between technological logics and environmental dynamics can play a key role in creating systemic solutions that consider environmental externalities of cities as engines of economic growth. Explicitly, ICT-based innovations (analytics, models, simulations, decision support systems, etc.) could be instrumental in improving energy efficiency and thus mitigating climate change in the context of smart sustainable cities, if they become mainstream strategies for urban development. It follows that ICT development must be mobilized and directed at promoting sustainable development in an increasingly technologized, computerized, and urbanized world. There are studies corroborating that ICT could do a lot more to help push the urban world in this direction (Bibri and Krogstie 2017a, b). Unsurprisingly, urban sustainability has become at the center of focus in terms of exploiting and unlocking the potential of ICT as an integrative and constitutive technology for making substantial contributions to environmental sustainability across all urban domains (see Chap. 9 for further details). All in all, thinking systemically in the context of urban sustainability entails adopting a holistic and intuitive perspective driven by the pursuit of consciously going with the grain of nature and making visible possible places for actions that enable to develop and implement the frameworks necessary for the translation and operationalization of environmental sustainability into concrete endeavors, initiatives, and practices in a more intelligent way.

6.6 Issues of System Structure: The Technological Component of Smart Sustainable Cities

Just as it is associated with, yet at varying degrees, every subsystem of the system of smart sustainable city, environmental sustainability can be affected by every aspect of the planning and development of such city. This is in the spirit of systems thinking as a discipline for seeing wholes, which provides a better understanding of the system based on the relationships of its parts with each other and with other systems—rather than in isolation. To reiterate, systems thinking constitutes a framework for seeing interrelationships and dynamic changes rather than things and their characteristics. This is of high relevance to ICT and its growing role and significance in smart sustainable cities, of which the technological infrastructure constitutes a great part. Indeed, ICT as an enabling, integrating, and constitutive technology pervades all the domains of smart sustainable cities. In more detail, this class of cities is characterized by extreme levels of ICT ubiquity and massive use, i.e., data sensing, information processing, and wireless networking in terms of sensor technologies, data processing platforms, cloud computing infrastructures, middleware architectures, and multiple networks are widely deployed, deeply embedded into the very fabric of urban systems (see Chap. 3 for further details). This must have some sort of deep effects on other sys-systems of smart sustainable cities, as well as on the other systems such cities interact with or are nested in. Accordingly, what further complicates the matter as regards to the reliance of smart sustainable cities on ICT of pervasive computing to advance environmental sustainability is that this kind of urban development is fast becoming the new reality with the very massive proliferation of the core enabling technologies of ICT of pervasive computing that are most likely to pose significant risks to environmental sustainability (Bibri and Krogstie 2016). There exist intricate relationships and tradeoffs among the positive impacts, negative effects, and unintended consequences of ICT of pervasive computing in relation to the environment—flowing mostly from the design, development, use, application, and disposal of ICT products and applications throughout smart sustainable cities (Bibri and Krogstie 2016). The adverse environmental effects of ICT of pervasive computing remain unprecedentedly complex and extremely problematic to deal with in the context of smart sustainable cities. They involve direct effects, indirect effects, rebound effects, systemic effects, and constitutive effects (see Chap. 10 for a detailed account and discussion). However, from a broader perspective of sustainability science, as informed by a systems view, several scholars have highlighted the need to probe the root causes of the unsustainability of the predominant paradigms of technological, economic, and societal development. For instance, Brown (2012) contends that sustainability science must involve the role of ICT in as well aggravating the unsustainability of social practices (e.g., urban planning and development) as in tackling the complex problems (e.g., multidimensional effects on the environment) such practices generate, and also include the study of the societal structures as to material consumption. In all, unless smart sustainable cities can “be reoriented in a more environmentally sustainable direction, as they can not, as currently practiced, solve the complex environmental problems placed on their agenda as a holistic approach to urban development (Bibri and Krogstie 2016), they risk becoming fallacies and paradoxes in the long term. ICT solutions should in this regard be carefully implemented in conjunction with other measures as well as policy and planning instruments to yield the desired outcomes as to the environmental gains and benefits expected to result from the development and implementation of smart sustainable cities. (see Chap. 10 for a detailed discussion with some suggested measures for, and design approaches into, mitigating the environmental risks posed by ICT of pervasive computing).

6.7 On Deep Urban and Environmental Sustainability

In light of the above, urban sustainability aims toward the wholeness of cities—a holistically, reflectively, and knowledgeably conceived approach to responding to the timeless challenges and mounting problems facing cities, as well as to making choices and decisions and taking actions pertaining to ecological modernization and thus societal transformation. The basic premise of urban sustainability is the long-term goal of keeping the socio-ecological system of city in balance over the long run: the city strives to sustain the ecological system along with the societal system, to draw on Bibri (2015). Thus, as a goal set far enough into the future, urban sustainability allows us to determine how far away we are from it and to calculate how—and whether—we will reach it. Crucially, it provides a framework for addressing problems based on upstream rather than downstream solutions so that they stay solved and importantly, do not create further problems. That is, it advocates the solutions that focus on the root causes of the original problems rather than on those that focus on the symptoms of the problems, attempting to only react to their effects. Currently, the underlying crises of urban environmental and social disintegration continue to worsen at an alarming rate, while most efforts to address them are failing to provide adequate solutions—in other words, huge efforts and colossal resources seem to be deployed or devoted to rethinking the current complex problems rather than solving them from the source (Bibri 2015). A large part of this conundrum pertains to the way new technologies are being designed, produced, applied, used, and disposed of. Consequently, there is a risk that as fast as we discover "innovative" solutions—usually of one-dimensionality or as quick fixes to rather complex problems—we reject them because they become no longer valid, if not useless, after a certain period of time (Bibri 2015). We are known for our fallibility and imperfection no matter how hard we direct our technical brilliance and energy of insight into understanding our dynamic interaction with nature. All our judgments are not to be forgotten to be the work of humans who, despite their marvelous intelligences and powerful minds, get tired, uninterested, and drained so easily, and wish that they could undo on new mornings at least part of what they did yesterday (e.g., Bibri 2015; Foster 2001). This relates particularly to

ICT innovations given their socially disruptive nature, especially ICT visions are incredibly enticing and motivating when strongly disruptive technologies emerge into and permeate society. However, experiences continue to show that it is not easy to look at the whole system when attempting to implement sustainable development as a strategic process to achieve the goals of sustainability; people have rather a tendency, or are sometimes forced, to look at a single element of the system because of what the prevailing economic, political, and institutional structures and practices dictate—in technologically advanced societies. That is, societal and strategic actors, e.g., strategists, planners, visionaries, policymakers, research leaders, technologists, and so on, tend to focus on a few goals, while neglecting other goals or shunning being specific on the details of the objectives set to attain these few goals. Urban sustainability is rather about the strategic embrace of holistic thinking about and deep understanding of the whole city system necessary to move toward and realize a sustainable future.

Deep environmental sustainability is about internalizing material and systemic limits, i.e., fully understanding and living within the carrying capacity of the ecosystem, a problem which is more fundamental than demanding everyday life choices, innovative solutions, enhanced social practices, and integrated approaches. In this regard, advances in ICT, which can enable, or holds great potential, to address many environmental challenges and enhance everyday life and social practices in cities—have to be grounded in environmental philosophy and ecological intelligence. From a general perspective, advances in science and technology should mirror creative deployments by scientists and technologists of some of their crucial skills and wits in life-intelligent sense-making. This relates to critical environmental literacy. In relation to this, Stables and Scott (1999, p. 152) underscore the importance of a deep understanding of "how (and why) our scientific knowledge and technological and artistic endeavors are historically and culturally situated," which is concurrently a reawakened "wonder at the ultimate unknowability and finitude of life." Ecological limits should come to bear at the level of consciousness and the object of direct experience of humans, on the way they comport themselves in representing, viewing, understanding, realizing, and acting in the world. Hence, it is essential to bring ecological values to the forefront of human intelligence and technical brilliance, and to pay enough attention to the subtle links between humans and nature in ways that find pathways to live mutually with it by humans reshaping themselves to fit a finite planet since it cannot be redesigned to fit their infinite needs. Indeed, deep sustainability is "not a measurable condition or trend, but a particular way of being humanly alert to and alive through the world." (Foster 2001) This occurs through, among other things, ensuring that human activities do not limit the range of environmental options open to future generations, which entails pursuing a rational approach to science, technology, innovation, and policy in terms of integrating environmental protection and integration into decision-making on many scales, whether concerning cities or other spheres of society. Comparing deep (environmental) sustainability to operational (environmental) sustainability, Foster (2001) points out that the former entails "not judging as if there were no tomorrow," while the latter, which is about creating patterns of using ecosystems and its resources and services in ways to ensure living within the material and systemic limits of the planet, is about "not living in the economic and political dimension as if there were no tomorrow." Positively, deep environmental sustainability entails understanding "the claims…of the whole succession of tomorrows in which we are bound up" and "using our minds as…if our perspectives were not always more or less subtly shaped by the pressures of our wants and drives" (Foster 2001). Consequently, claimed progressions toward realizing the imagined future or long-term goal of environmental sustainability solely through technological innovations are associated with rhetorical features—rather than performative and generative aspects. That is to say, the expectations being placed on the potential of ICT of pervasive computing for advancing environmental sustainability are far from being performed in establishing binding policy agendas, nor generative in instigating or bringing about concrete plans for strategic action (Bibri 2015). In other words, transforming our environmentally detrimental technology into one that can sustain ecological progress depends on a radical shift in institutions, social value orientation, political beliefs, ecological modernization of mind, and economic mindset. Environmentally sustainable technologies necessitate that the principles of deep ecology establish the framework for the development of technology and related research and innovation policy. However, the role of technological development as the unquestioned objective of technology policy and the trade-offs between environmental goals and often short-term societal benefits of technological innovation remains real dilemmas in technologically advanced societies. As argued by Foster (2001, p. 159), "living with the grain of nature" is an issue only for humans, and "by the same token, any understanding of our so living will be a representation of ourselves in relation to the rest of the world, one which we construct and which has then to be applied as a criterion to the pattern of our ongoing actions."

Of importance to the evolution of sustainability as a holistic thinking paradigm is that economic development in society needs to systematically incorporate environmental and social factors. But of crucial importance to the evolution of environmental sustainability is that it should take into account the environmental-damaging externalities associated with the intensive use of energy and concomitant GHG emissions, with a particular emphasis on the multidimensional effects of ICT of pervasive computing on the environment. These effects derive from the design, development, use, application, and disposal of novel ICT products and applications, in particular in the context of smart sustainable cities of the future. Especially, ICT is one of the main driving forces for ecological modernization, an inevitable stage in the development of industrially and technologically advanced societies.

6.8 Key Concepts of Systems Thinking and Their Relevance to Smart Sustainable Cities

Many of the concepts of systems thinking and complexity science have been widely applied and demonstrated in different fields to varying degrees, depending on the domain on focus. In this chapter, we will cover only five of these concepts: (1) chaos theory, (2) open and closed system, (3) data-information-knowledge, (4) cybernetics, and finally (5) system interaction, due to their high applicability to smart sustainable cities as complex systems. We discuss these concepts through comparing the points of view of the authors who have contributed to the relevant literature, attempt to develop some of our own, and then examine the relevance of the concepts in question to smart sustainable cities.

6.8.1 Chaos Theory

Complexity theory originates in chaos theory. Chaos theory aims to explain complex systems that consist of a large number of mutually interacting and interrelated parts in terms of these interactions and relationships. It is a field of study that is concerned with the underlying patterns and highly complex behavior behind seemingly chaotic or unpredictable systems. Generally, it is concerned with nonlinear, dynamic components of systems, whether stable and unstable. Seen from this perspective, chaos theory was created as an attempt to comprehend and learn about world phenomena beyond the normal perceptual limits of human experience and knowledge. It came out of a need to tackle complex issues associated with system organization in a variety of fields, such as physics, biology, ecology, psychology, and computing. Examples of such systems include: neural networks, human brain, cultural system, natural system, and city. These kinds of systems cannot be explained through the standard laws of physics (cause–effect or linear models) because they exhibit unpredictable patterns and behaviors, which require systems thinking approach to model their seemingly random components due to the sensitivity of the related system to initial conditions and small changes that can lead to unexpected changes and unplanned results, i.e., environmental crises caused by anthropogenic factors or subsequent to the instrumental rationality of industrial economy. According to Gribbin (2005), chaos theory is, at its heart, concerned with the initial conditions of a system and the effect of positive feedback on changes in that system. More specifically, Walonick (1993), chaos theory is an attempt to explain and model the seemingly random components of a system and recognizes that systems are sensitive to initial conditions in that small differences or even the tiniest variation in such conditions can produce large changes or unpredictable patterns in the system, leading to widely different results in the later state of the system, This implies that inadvertently neglecting other system variables (mostly unperceived or hidden) could cause failure in controlling the overall state of the system. Thus, neither precise starting conditions of a system can be known nor can an accurate prediction be possible. Meteorologist Lorenz (1963) used a microcomputer to simulate weather patterns in 1960 and while inputting initial starting conditions to the computer, he inadvertently rounded one of the numbers to three, instead of six decimal places, and this consequently produced rapidly divergent simulations of weather patterns. Consequently, he concluded that small changes could be used to manipulate large weather patterns and that this was the reason for the failure of long-term forecasts. As chaos theory provides mathematical methods required to describe chaotic and nonlinear systems, and allows some general prediction of a system's complex behavior, traditional predictive mathematical models have, as Walonick (1993) points out, incorporated error into the model to explain seemingly random fluctuations and components of a system. That said ecologists have modeled population growth using a logistical difference equation which shows for many initial starting parameters that the traditional growth model—a population grows, exceeds its optimal steady-state level, and then experiences oscillations of diminishing magnitude as the system approaches equilibrium, in addition to other unpredictable behaviors relating to starting values over time space (Walonick 1993). Chaos theory has been experienced, applied, and demonstrated in many scientific disciplines.

Chaos theory is essential to understanding social systems as to the linkages and interactions between the parts that comprise their entirety, as well as to learning from experience, through their chaotic and dynamic environment as to maintaining their structures and purpose. This is at the core of smart sustainable cities in terms of applying knowledge associated with unlocking the potential of ICT to respond to the challenges of sustainability and urbanization as a result of the current (and potentially emergent) unstable changes in their collective patterns and behaviors with regard to climate change. Here the use of ICT enables and catalyzes the adaptiveness of smart sustainable cities by using their capacity to change and learn from experience through integrating the underlying technological and urban components in ways that improve and sustain their contribution to the goals of sustainable development toward sustainability in their evolution (Bibri and Krogstie 2017b). Further, the established structures of large systems are usually less able to change as the inertia resulting from their size makes it difficult to introduce planned changes (Walonick 1993). Large systems with well-established patterns may produce unpredictable behaviors due to potentially human-induced effects on the process of their dynamic interaction with the environment. They are open systems whereby the stability of the structures is subject to changes driven by the external measures and conditions of the environment, which make them less able to adapt to internal system changes. It is apparent that the objective of chaos theory is, through the applicability of its associated knowledge, to enlighten about the nature of potential change in social organizations (Walonick 1993). Understanding the nonlinear relationships among, and the dynamic interaction between, system components is undoubtedly critical in major changes needed by human society to sustain its evolution. Cities as social fabrics epitomize the microcosm of human society in terms of encapsulating in miniature its characteristics and structures as to environmental change, economic development, and social transformation.

Compared to Walonick (1993), Kellert (1993) describes chaos theory as "the qualitative study of unstable aperiodic behavior in deterministic non-linear dynamical systems." He includes other elements into his definition—deterministic, qualitative, and aperiodic aspects. From his perspective, chaos theory seeks to identify patterns in behavior over the course of long term and hence the focus is on qualitative changes. A close examination of the above-stated definitions of chaos theory depicts its association with complexity theory. This theory concerns itself with chaotic, nonlinear, and dynamic systems with highly complex behavior and unpredictable patterns that do not follow clearly repeatable pathways. Furthermore, a little variation in the initial conditions of a system may lead to unpredictable sudden change in that system in a way that visible patterns may disappear and new patterns unexpectedly emerge. Arguably, there could be an order in the patterns of behavior of complex systems, yet perceived as chaos because such systems cannot be fully understood due to the limitation of human intelligence and technical brilliance. This is due to relativism inherent in scientific paradigm, which relates to the philosophy and sociology of scientific knowledge (e.g., Foucault 1972; Kuhn 1962). Hence, a system behavior in a chaotic state of change is likely to exhibit some kind of order that is not graspable or simply imperceptible by humans. To put it differently, a chaotic behavior does not indicate a lack of order, but rather the order is difficult or impossible to describe in simple terms and requires complex narrative description (Kellert 1993). As echoed by Hayles (1991), chaos is sometimes viewed as extremely complicated information, rather than as an absence of order.

Regardless, the kinds of systems explored under chaos theory are dynamic, respond to the environment, and are often inherently unstable; however, where stability occurs, it is fragile and may be disrupted by small environmental changes (Kellert 1993). Expanding on the aperiodic aspect revealed by Kellert (1993), it is highly complex and permanently sensitive to small perturbations, as chaotic systems do not manifest any fixed, repeatable values (never exact copies and in a state of flux) and patterns (emerge, persist for a while and then die off to be replaced by apparent randomness and then the birth of new patterns), although they remain within a fixed, definable space. By and large, Kellert's definition proposes that the study of chaos theory is above all qualitative.

In contrast to Walonick (1993), Tsoukas (1998) suggests that chaotic systems are deterministic in that there is one unique end point or goal of the system that can be mathematically derived given the initial conditions. This can be explained by the fact that small changes in the initial conditions may generate very different end points in case of open systems. But if we consider an isolated system where initial conditions are determined without any interaction with the environment, then we can clearly determine the end point. In this view, determinism does not imply total predictability, despite the perception of having the ability to predict the later state of the system. Indeed, as pointed out by Thietart and Forgues (1997), cause–effect and linear links, albeit deterministic, cannot be sometimes repeated. Although, determinism is an element of his definition of chaos theory, Kellert (1993) argues that chaos theory may not be deterministic but its interpretive application may be justifiable.

Chaos theory is associated with complex systems as perceived by humans who can understand and discern linear and cause–effect links (basic law of physics and agreed upon mathematical methods) as well as changes in patterns and behaviors over time beyond these links. In complex systems, the complexity is manifested through constant intervention involving new conditions, new dynamics, new emergent properties, unpredictable patterns, unrepeatable values, and environmental changes. All these manifestations are apparently impossible to be clearly perceived, objectively interpreted, and systemically interconnected. No matter how humans can use and harness their intelligence and wisdom in crafting powerful simulations using the most cutting-edge technologies, chaotic patterns and unpredictable behaviors will still appear as such in larger systems and their interaction with the environment—merely because this is the only way we can "scientifically" understand complex phenomenon when it comes to systems exhibiting chaotic patterns and behaviors.

Nevertheless, chaos theory could be further developed and combined with other nonsystem and system theories so as to generate richer theoretical perspectives based on interdisciplinary and transdisciplinary scholarship, with the primary aim of developing new, robust methods that can enable humans to transcend their (limited) perception as to how and why they perceive multifaceted phenomena the way they do in this context. Especially, this makes them more often than not realize that their understanding, knowing, and learning are inherently deficient and thus the truth only exists in relation to culture, society, or historical context. To understand what is larger than us and how that can be feasible without totally understanding the parts that comprise the entirety of that which is larger than us seems to be unattainable and even unthinkable in the realm of prevailing scientific discourse. Currently, we are still struggling with figuring out what to do about the total chaos that has been caused by the so-called civilization. And it has taken almost two centuries to realize the unintended consequences of this civilization in terms of the environmental crises and social decays it has generated. It might take a very long time to restore what has been damaged as exhibited in the chaotic behavioral patterns of our cities and other human engineering systems.

Like other systems thinking concepts, chaos theory is of applicability to many fields in terms of systems and their changing patterns and behaviors. Key concepts from chaos theory such as initial conditions, strange actors, choices and events, bifurcation, connectivity, iteration, and so on can be used in the development of interpretive approaches into smart sustainable cities as part of research endeavors and urban practices. These concepts can be of valuable support in developing a coherent and concrete interpretive framework for the interaction between the subsystems of smart sustainable cities and their collective behavior over time. This relates to narratives associated with describing the different levels of complexity surrounding smart sustainable cities. One advantage of such framework is to bring about consensus between various narratives in the domain of urban planning and development. Further, the application of chaos theory entails a story that traces a historical path, identifies the unexpected and the boundary effects of the subsystems of smart sustainable cities on their own organization, and analyses the effects associated with the dynamic interaction of these subsystems that is an important dimension of such cities. Also, chaos theory as a sensitizing tool has the potential to identify patterns in the interactions between smart sustainable cities and the environment in terms of the effects and influences on their own evolution. It is indeed an interpretive model for understanding the complexity of such interactions. Besides, the interpretive research in several city-related disciplines is usually concerned with the selection of a method for conducting the research and a framework for interpretation.

It is of crucial importance to understand the starting conditions of smart sustainable cities as systems when an urban development strategy is developed and implemented, as this understanding is likely to shape the later state of such systems as to generating potential unpredictable behavioral patterns in ways that it could result in positive outcomes, or at least steers clear of any negative outcome due to potential unstable changes. In this sense, the situation resulting from the chaotic and dynamic behavioral patterns of smart sustainable cities and their interaction with their environment could yield desired outcomes that can be translated into a drastic transformation in terms of sustainability.

Chaos theory is derived from complexity science and can be applied as a metaphor and model for understanding complex behaviors and unstable changes. Smart sustainable cities are part of, and affect, the behavior of the environmental (natural system). The influence of their development and implementation occurs in ways that may not be entirely predictable. The metaphors and models applied to organizations are transferable to the study of smart sustainable cities within the environment. As derived from chaos theory, they constitute the scaffolding that allows the researchers' audience in the domain of urban planning and development to make sense of the interaction between such cities and the environment in order to holistically view and examine urban phenomenon and draw lessons that may be applicable in other circumstances and conditions. Chaos theory could be applied to the analysis of quantitative data in the context of urban development strategy studies. The complex interactions between actors, technologies, and urban typologies that take place in the development and implementation of smart sustainable cities as strategies and the environmental change in response to such cities may be open to interpretation within a chaos theory framework.

To conclude, chaos theory is applied to phenomena whereby there are interactions between many factors and random components of chaotic and nonlinear dynamic systems that exhibit unpredictable patterns/behaviors and generate unrepeatable values. It is of value to encourage research opportunities and to conduct studies that focus on the applicability of chaos theory as part of complexity theory to smart sustainable cities.

6.8.2 *Open and Closed System*

Generally, an open system is a system that has input and output flows, representing exchanges of energy, material, or information with its surrounding. In other words, it exchanges feedback and continuously interacts with its external environment. This interaction involves inputs, outputs, processes, goals, communication, assessment, and learning. In open systems boundaries, external environment and equifinality are deemed to be key characteristics. Generally, the concept of equifinality explains that the same later state in the system can be achieved by using a variety of starting conditions or different processes. This means that different initial conditions can lead to the same results. In contrast, a closed system is a system that is isolated from the environment (no interaction) to some degree, as there is no system that can practically be completely closed. In physics, a closed system can exchange energy and work, but not matter, with its surroundings while an open system exchanges energy, work, and matter with the environment. The interaction in a closed system occurs only among the system components and not with the external environment. von Bertalanffy (1968a) points out that conventional physics deals only with closed systems which are considered to be isolated from their environment; however, we find systems which by their very nature and definition are not closed systems. Open systems like living organisms tend to regularly and continuously take in inputs from the environment and release output to it through a continuous inflow and outflow. In so doing, living organisms as open systems build up and break down of components so long as they are alive, in a state of chemical and thermodynamic equilibrium (von Bertalanffy 1968a).

The inception of the open system concept has significantly contributed to bringing light to many mystifying and puzzling issues related to world phenomena in physics, biology, and society. The concept has led to important general conclusions regarding the principle of equifinality. This denotes that in any closed system, the final state is unequivocally determined by the initial conditions, e.g., the motion in a planetary system where the positions of the planets at a time t are unequivocally determined by their positions at a time t (von Bertalanffy 1968a). From an organizational perspective, management can achieve the same results by using different sets of inputs, resources, processes, strategies, customers, suppliers, and systems. In contrast, the same final state may be reached or determined in closed systems from specific initial conditions. Some political and organizational systems known as closed systems (e.g., bureaucracies) have one way to do things regardless of the usefulness of the processes undertaken to generate the results. In addition to the general conclusions drawn about equifinality, according to the second principle of thermodynamics, the general trend of events in physical nature is toward states of maximum disorder and leveling down of differences, while the living world shows that in embryonic development and in evolution a transition is toward higher order, heterogeneity, and organization (von Bertalanffy 1968a). Based on the literature, in all irreversible processes, entropy must increase. And in open systems, there is a production of entropy due to these processes and an import of entropy which may be negative, so the apparent contradiction between entropy and evolution disappears. This can be manifested in a living organism that may, based on law of physics, import complex molecules high in free energy (negative entropy) or avoid the increase of entropy, which will allow living system to maintain itself in a steady state and may even develop toward states of increased order and organization. Walonick (1993) supports this view as he claims that open systems tend toward higher levels of organization and order (negative entropy), while closed systems can only maintain or decrease in organization and order. In contrast, the change of entropy in closed systems is always positive; order is continually destroyed (von Bertalanffy 1968).

According to Bellinger (2005), systems may be characterized as either closed or open. A closed system is one that does not need to interact with its environment to maintain its existence. Seen from this description, and compared to Bertalanffy, the interaction of open systems is a condition to maintain existence in the environment, whereas this condition is not necessary for closed systems to exist since they do not need to interact with the outside environment. Therefore, Bellinger (2005) claims that open systems are organic and must interact with their environment in order to maintain their existence. This can be manifested in living organisms, such as humans, plants, and animals that cannot survive in the environment without taking in oxygen, water, and food. When living organisms take in these inputs, they, in return, produce waste products as an output to be released to the environment. The examples of the furnace, filling the water glass, adjusting the shower tap are considered to be open systems, as the elements in the external environment are deemed to have an effect yet are not elaborated (Bellinger 2005). Mechanical systems, clockwork mechanism, or a battery-driven electric motor are examples of closed systems. Furthermore, Bellinger (2005) points out that an open system may interact with its environment in a growth or balancing fashion as often the time of changing influence between that system and the environment may be of such lengthy duration or of such minimal nature so as to limit its need to be considered.

Bellinger (2005) and von Bertalanffy (1968) share the opinion that it is often more appropriate to consider a system as a subsystem of some larger system with which it must interact in some way. Atoms interact with molecules, molecules with cells with, and cells with humans and animals, and so on. Nevertheless, taking the larger system into account is, as indicated in general system theory, unnecessary for understanding the operation of its parts in isolation (Bellinger 2005). Generally, all systems can be both subsystems or parts of larger systems and consist of subsystems or parts at the same time. Furthermore, Bellinger (2005) states: “One could study hydrogen and oxygen in isolation from each other forever and never discover the characteristic of wetness. Wetness is an emergent characteristic of the mutual interaction of hydrogen and oxygen when combined to produce the molecular form called water. One has to study the system to get a true understanding of wetness. Studying the parts will not provide an appropriate understanding.” An open system is characterized by the dynamic interaction of its components, while the basis of a cybernetic model is the feedback cycle (Walonick 1993).

A system is composed of subsystems or parts interacting to achieve a common goal. Whether the system is closed or open, there is always an interaction process that maintains its inflow and outflow, either between its parts or in relation to the environment. The nature of the interacting elements determines how the system can be categorized as an open system or closed system (social systems vs. mechanical system). The condition of interaction contains even the existence conditions of open systems so their survival is bounded by how properly and efficiently they interact with the environment. If humans fail to inhale oxygen out of the atmosphere and exhale carbon dioxide into the environment, they die and then vanish. Similarly, some organizations if they fail to maintain interaction with the market conditions and structure by not delivering the demanded products and services to consumers, they eventually depart from the business environment leaving the space for other organizations that maintain the strategic behavior needed in the interaction with the competitive marketplace. However, the interaction can be voluntarily or instructed by other systems to reach a certain outcome depending on the nature of the systems being interacted, e.g., smart sustainable cities in terms of its interacting environmental, physical, social, and economic subsystems to maintain their existence at a certain level (i.e., sustainability). In this case, an isolated open system has no meaning or value if there is no interaction at all. Still, the components of smart sustainable cities (infrastructures, facilities, buildings, networks, resources, systems, citizens, etc.) need to communicate and so are supposed to be physically and logically connected to allow the interaction.

Overall, open systems refer to systems that interact with each other in an external environment, whereas closed systems refer to systems that do not interact with the outside environment in which other systems exist. Also, systems are usually open to some and closed to other systems and are subject to changing influences and environmental behaviors and conditions. All systems, whether open or closed, have boundaries which are usually difficult to identify due to the complexity and dynamic aspects of complex systems. Through these permeable boundaries, open systems exchange feedbacks in attempts to communicate with the environment and other systems. Unlike open systems, closed systems have hard boundaries through which information and energy are hardly exchanged. For example, some organizational design imposes structures with closed boundaries as that in bureaucracies and monopolies as systems. According to Huntley (2003), science, education, and our present established scientific theories (with accompanying mathematical verification) promote closed systems. Scientific methodology closes off systems and laws, giving rise to the false notion that physical laws and constants are unchallengeable and immutable (2003).

The concept of open and closed system has applicability in many disciplines and fields, e.g., biology, physics, social science, computer science, biomimicry, ICT, and urban development. Here we are concerned with its application in smart sustainable cities in terms of the interaction of their components as well as their interaction with the environment. One can think of several examples of open and closed systems pertaining to smart sustainable cities, whether in relation to the integration of urban systems as operating, organizing, and maintaining processes of urban life (e.g., infrastructures and facilities and public and social service system, built and natural environment, economic system and political system, innovation system and academia/industry, academia and industry, governance and policy, and governance and environmental management) or in relation to the coordination and collaboration among urban domains (e.g., energy and the environment, traffic and transport, traffic and mobility, land use and transport, health care and ICT, education and ICT), in addition to the interaction between all of the urban systems and the natural systems. The basic idea is that there are numerous subsystems of smart sustainable cities that can be described as open or closed systems for the way they are designed, operate, function, and/or evolve. For example, some subsystems of smart sustainable cities are open to public organizations, private companies, and/or citizens and others are closed to these constituents due to some predefined hierarchical structures or security reasons. In relation to this, there is growing and strong evidence that open data (and hence governmental agencies and departments) in the context of smart sustainable cities can help city governments in promoting informed participation, transparency, information equality, and shared knowledge among citizens and experts from different organizations, in addition to facilitating the endeavor to collectively reflect and find solutions to the environmental, social, and economic challenges of sustainability and urbanization (see Chap. 5 for further discussion). Furthermore, from an open system standpoint, without a clear understanding of smart sustainable cities in terms of the underlying internal and external interactions, urban planners, designers, engineers, and administrators are likely to focus their attention solely on the behaviors and events associated with the problems stemming from the physical structure, economic model, or technological infrastructure—rather than on the problems associated with the interaction between the subsystems of such cities with one another and with the external environment, which may cause environmental problems as a result of taking in inputs and releasing some sort of outputs depending on the goals set to be accomplished by the different entities comprising the city. To effectively solve problems related to any type of complex system, it is critical to consider a systems view that provides a deep level of understanding which allows to identify the real causes of the system problems in terms of interactions and transactions and accordingly devise upstream solutions to solve them.

Smart sustainable cities are regarded as open systems that take in resources from their environment and then process them in some way using a combination of human, information, and industrial systems to produce a wide range of physical and technological products and services spanning numerous urban domains and sub-domains. These pertain to urban systems which operate, organize, manage, and plan urban life in ways that improve and sustain the contribution of such cities to the goals of sustainable development toward achieving sustainability. Accordingly, such cities maintain themselves at a certain level through the interaction with their environment as well as between the subsystems they are composed of. In such cities, the relationships, transactions, reciprocal influences, and formal boundaries are of particular importance in the context of sustainability. For example, the ICT infrastructure of smart sustainable cities as a set of big data and context-aware applications, coupled with human systems, interact in a synergistic way to ultimately enhance their operation, function, and planning through control, optimization, automation, evaluation, and management in line with the goals of sustainable development. Underlying the idea of open systems in this context is that cities interact with their environment in a complex series of interrelated loops and reciprocal feedback, and their existence depends on how well their behaviors align with their environment. The external environment usually involves a wide variety of influences that can affect cities as regards to their technological, economic, social, physical, infrastructural, spatial, and ecological subsystems.

6.8.3 Data-Information-Knowledge

Data-information-knowledge hierarchy has been approached from different perspectives. To this hierarchy, wisdom is sometimes added to become of what is known DIKW hierarchy. It is one of the fundamental and widely recognized models in the knowledge-based systems. Further, information is defined in terms of data, knowledge in terms of information, and wisdom in terms of knowledge, if wisdom is included depending on the field being studied. According to Rowley (2007), DIKW hierarchy is usually used to contextualize data, information, knowledge, and wisdom with respect to one another, and to identify and describe the processes that transform elements lower in the hierarchy into those above them. Many attempts have been undertaken by different authors to normalize the transformation processes in attempts to create a widely accepted distinction between the first three components of the hierarchy. However, the mostly agreed upon assumption is that data can be used to create information and information can be used to create knowledge.

There are various definitions of data, information, and knowledge offered based on their applicability in different fields, including the following:

Data:

- Data has no meaning or value due to the lack of context and interpretation (Bocij et al. 2003; Groff and Jones 2003).
- Data are discrete or objective facts which are unorganized and unprocessed, thereby conveying no specific meaning (Bocij et al. 2003; Pearlson and Saunders 2004).

Information:

- “Information is data that have been shaped into a form that is meaningful and useful to human beings” (Laudon and Laudon 2006, p. 13).
- Information is a form of organized data that has meaning and value to the recipient (Turban et al. 2005).

Knowledge:

- “Knowledge is an intrinsically ambiguous and equivocal term” (Barnes 2002, p. 3).

- "Knowledge is the combination of data and information, to which is added expert opinion, skills, and experience, to result in a valuable asset which can be used to aid decision making" (Chaffey and Wood 2005, p. 223).

Ackoff (1989) proposes a hierarchy including the following levels: data, information, knowledge, understanding and wisdom. To the hierarchy previously mentioned, Ackoff adds understanding as another element and was later criticized by Bellinger et al. (2006) who suggest that understanding is not a separate level, but rather it supports the transition from each stage to the next, so moving from data to information involves understanding relations, moving from information to knowledge involves understanding patterns, and moving from knowledge to wisdom involves understanding principles. Their suggestion is based on the premise that understanding is present in all elements of the hierarchy, but in different forms, which is considered as reiteration of the hierarchy in other sources. Ackoff (1989) defines data, information, knowledge, understanding, and wisdom and explores the transformation processes between these elements. Although, most of these transformation processes are described from an information system perspective, Ackoff initially described the elements of his hierarchy as a content of the human mind. Based on his order, wisdom is located at the top of a hierarchy of elements and from which is derived understanding, knowledge, information, and data as at the bottom of the elements. Ackoff defines the four elements, in addition to intelligence, and their associated transformation processes as follow:

- Data are defined as symbols representing properties of objects, events and their environment and are not useful until they are in a useable form, and the difference between data and information is rather functional than structural;
- Information is contained in descriptions, answers to questions that begin with such words as who, what, and when, and inferred from data. Information systems generate, categorize store, retrieve, transfer and process data;
- Knowledge is know-how, expertise, and experience, and what makes possible the transformation of information into instructions. Knowledge can be obtained either by transmission from another who carries it as tacit knowledge, by instruction, or by extracting it from experience;
- Intelligence is the ability to increase efficiency and performance through manipulating knowledge; and
- Wisdom is the ability to increase effectiveness as it adds values (ethical and aesthetic values that are inherent to the actor and are unique and personal), which requires cognitive processes and mental functions regarded as judgments.

In an attempt to compare Ackoff's and Zeleny's models, we depict that Zeleny proposes enlightenment as an additional level at the top of the hierarchy. According to Zeleny (1987), enlightenment goes beyond wisdom (understanding why), and going further and attaining the sense of truth, the sense of right and wrong that is socially accepted, respected, and sanctioned. Table 6.1 illustrates the comparison between Zeleny's and Ackoff's models (Rowley 2007).

Table 6.1 Comparing Ackoff's and Zeleny's definitions of data, information, knowledge and wisdom

	Zeleny [34]	Ackoff [1]
Data	Know nothing	Symbols
Information	Know what	Data that are processed to be useful; provides answers to who, what, where, and when questions
Knowledge	Know how	Application of data and information; answers how questions
Understanding		Appreciation of why
Wisdom	Know why	Evaluated understanding
Enlightenment	Attaining the sense of truth, the sense of right and wrong, and having it socially accepted, respected and sanctioned	

Source Rowley (2007)

Another attempt to understand the hierarchy in question was undertaken by Jashapara (2005) and Choo (2006) who introduce the concept of signals. Compared to Ackoff and Zeleny who focused on the levels of the hierarchy, Choo (2006) focuses in his diagram (see Fig. 6.2) on the transformation processes between signals, data, information, and knowledge.

Choo (2006) suggests that data are often elements of larger physical systems, which gives clues about what data to notice and how they should be read, and calls the process which assigns meaning and significance to the perceived facts and messages, "cognitive structuring". Thus, the receiver of the data that determines whether a message is data or information determines the meaning based on some

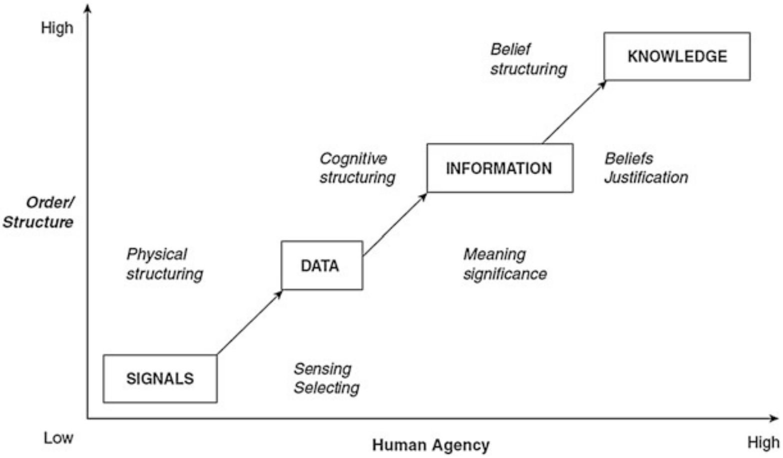

Fig. 6.2 Data, information and knowledge, according to Choo (2006). *Source* Rowley (2007)

form of association with experience. He concurs that information becomes knowledge through the process of belief structuring or the formation of justified beliefs about the world that is inferred from a lot of other criteria, such as culture, experience, and background, and so on. In addition, he deepens this development and identifies signals as the origin of data, and proposes the processes of sensing and selecting, together described as physical structuring, as transforming signals into data. Further to this point, Jashapara (2005) suggests that we use our experience to make sense of the signals that we acquire in the form of data from the external world through our sense organs. All these processes are associated with cognitive and mental functions that are part of cognitive psychology in which these processes encompass: sensation, perception, recognition, attention, memory, emotion, motivation, and problem-solving. The cognition process begins with stimuli-feedback response when sensing external objects and during information processing. Based on the hierarchy, the higher elements can be explained in terms of the lower elements by identifying an appropriate transformation process that occurs between two elements as we descend the hierarchy. Understanding the transformation processes from one element in the hierarchy to another (hierarchy of any kind) has been a real challenge for many authors in different fields, including information systems and data management.

The data, information, and knowledge hierarchy has different formulations in which the three elements are markedly considered as the key for it is an agreed-upon conception adopted by different disciplines for long. In addition, these elements are mostly arranged and classified in the same order, with the exception of some models that include other elements for clarification or development purposes as new disciplines emerge. Seen from this perspective, it could be conceivable to explore this hierarchy from different conceptual angles. For example, to create and structure data and information in any system, prior knowledge (expertise, skills, know-how) is required. Without the later, humans would fail to create any system based on one or more elements in the hierarchy of any kind. We invent systems using knowledge, understanding, intelligence, and wisdom as preliminary components in the whole design process of system creation. However, it is understandable that when we develop and use other systems that human can interact with like computer systems, the reversed hierarchy would not obviously be relevant before having the system developed, implemented, and up and running as a prior condition. Depending on the form of interaction between systems, information can be inferred from knowledge that can in turn nurture and emerge only within typical social and organizational environment accompanied with the appropriate cognitive and mental processes of human mind required in the interaction process with the outside environment. Therefore, the design should focus on all these systems to allow an effective interaction and transformation from one element to another in any kind of system. The reversed hierarchy would make more sense in case of exchange between what human carry as wisdom and expertise and the content of explicit knowledge codified in documents and databases, which emerges from information and data as approached from a knowledge management perspective.

There is a general consensus that knowledge is a very complex and sweeping concept. As a matter of fact, we have noticed many attempts of including other elements after the knowledge element in the hierarchy. This implies that the knowledge element is still not of clear scope and defined boundary (many other concepts are indeed not due partly to the systems thinking approach currently adopted by humans to perceive, understand, and learn about the world around us). From this perspective, a more qualitatively advanced approach to systems thinking may come to light as more discoveries in systems science will emerge, which are likely to be stimulated or spurred by the new integrated approaches associated with transdisciplinary scholarship and critical systems thinking. Also, with the combination of systems thinking concepts and levels in a field of study, knowledge concept may extend to include deep aspects of articulation and meaning that include other dimensions of a dynamic nature as it is the case for information with regard to computation and processing. In line with that, the transformation processes associated with the different elements of the hierarchy will be explained from new perspectives with high granularity as human understanding advances as to the relationship between the different levels of systems thinking continuum. The transformation processes between the different elements of the hierarchy should be seen from a systems thinking perspective and not defragmented relationships or levels. In particular, knowledge entails understanding, experience, skills, values, morals, aesthetics, practices, advances, collective learning, and so on. It is a very challenging task to combine all these elements to distill a common scope of knowledge and how it evolves and what it generates.

Data-information-knowledge as a systems thinking concept has applicability in different fields, e.g., big data analytics, context-aware computing, data management, and communication engineering. These are all of relevance to smart sustainable cities in terms of ICT and its role in advancing sustainability through employing innovative solutions and sophisticated approaches (e.g., intelligence functions and decision-support systems and related optimization strategies, simulation models, and communication models). The role of the data-information-knowledge hierarchy is central to the functioning of the ICT infrastructure of smart sustainable cities in terms of big data and context-aware applications. Such applications use communication models to code data to place them in databases and locate them for subsequent use in the form of meaningful information that can subsequently be coalesced, integrated, processed, analyzed, evaluated, and then deployed in the form of useful knowledge for making and supporting a wide variety of decisions pertaining to various urban domains and sub-domains (e.g., transport, mobility, traffic, environment, energy, safety, health care, education, planning, and design). In relation to big data applications, big data analytics denotes any vast amount of data that has the potential to be collected, stored, retrieved, integrated, selected, preprocessed, transformed, and mined for discovering new or extracting useful knowledge which can subsequently be evaluated and visualized in an understandable format prior to its deployment for decision-making purposes (e.g., a change to or enhancement of operations, strategies, practices, and services). Specifically, In the context of smart sustainable cities, big data analytics targets optimization and intelligent decision support pertaining to the control, optimization, management, and planning of urban systems as operating and organizing processes of urban life, as well as to the enhancement of the associated ecosystem and human services related to utility, health care, education, safety, and so on. Additionally, it targets the improvement of practices, strategies, and policies by changing them based on new trends and emerging shifts.

Big data ecosystems are layered software stacks, including data—processing engine based on a low—level database. From a database management perspective, a relational database makes information from the data stored within it. These data are presented in a certain format with a given syntax in dispersed spots (tables, charts, algorithms, etc.) so the relational database system relates the data to produce information depending on the requests placed by the database administrator. The meaning of any item of data in a database for a specific individual, team, or organization depends on the alignment between the data structure and the cognitive schema of the individual, team, or organization (Rowley 2007). This hierarchy brings meaning and value to the whole process of transformation of the different elements from one to another, and makes more sense when using information systems in an organization or as part of the ICT infrastructure of the city.

Furthermore, all the domains of ICT use one, two, or all the three of the data-information-knowledge hierarchy elements. These areas include the following:

- Human–computer interfaces which involve software user interface (operating systems and communication programs) and graphics design and development of human-friendly devices;
- Information systems which center on defining requirements, designing, testing, implementing, and maintaining information systems;
- Database management systems which focus on the design, development, modeling, configuration, evaluation, and implementation of information retrieval software programs;
- Information technology resource plans which entail the development of organizational information plans and the installation of computer systems; and
- System development through integration which is associated with managing organizational web presence, configuring and integrating e-applications, developing multimedia solutions, and configuring and merging decision-support systems.

6.8.4 Cybernetics

Cybernetics is the study of the communication and control of regulatory feedback in systems. It focuses on how anything digital, electrical, mechanical, and electronic controls its behavior, processes information, reacts to information, and changes or can be changed to better accomplish those three primary tasks. Cybernetics as the theory of control mechanisms in technology is founded on the concepts of information and feedback. Cybernetics was a product of a remarkable set of discoveries concerning the nature of self-corrective or self-regulating machines. The term “cybernetics” has been used interchangeably with that of systems theory. According to von Bertalanffy (1969) systems theory is frequently identified with cybernetics. This term was coined by Norbert Wiener in reference to the, “entire field of control and communication theory, whether in the machine or in the animal” (Wiener 1948, p. 11). Wiener publicly used the term Cybernetics in March 1946, at the first of the Macy conferences, entitled, “Feedback Mechanisms and Circular Causal Systems in Biological and Social Systems” (Lipset 1982, pp. 179–181). In the Macy conferences, cybernetics was introduced as an interdisciplinary field, which led to a great enthusiasm among the scientists who attended the conferences, including Bateson who was content with the adequate depth of the ideas offered as he realized that a conceptual framework for the biological and social sciences was emerging. Bateson (1979) points out that Cannon’s discovery of homeostasis in the maintenance of the chemical balance of the blood had already revealed the fundamental principles of the self-regulation processes. The research in this area was more rigorous and focused, and its premise was to build devices that could monitor their own performance, self-regulate, correct for deviations and changing conditions, steer their behaviors, and adjust their goals. All these functions were based on the properties of closed self-corrective circuits—feedback mechanisms. Bateson had a significant contribution in the advent of cybernetic ideas as an interdisciplinary field. Cybernetics offered a more rigorous formulation of theoretical concerns in his work. He states: “If we could in any real way identify or analyze *the causation* of growth, biology would become a branch of physics” (Bateson and Beatrice 1928, p. 209). At the general level, cybernetics theory opened new horizons for the examination and explanation of living systems and offered the possibility of applying a variety of concepts originating in mathematics and engineering used in many disciplines, such as biology, anthropology, social science, and behavioral science. Bateson refined the newly developed lexicon of cybernetics so that it could be used with both scientific rigor and poetic imagination (Wilder-Mott and Weakland 1981).

Rosenblueth et al. (1943) introduced a new paradigm in science, according to which one seeks an overarching theory to include machines and organisms; the theory would clearly involve ideas of information, control, and feedback. Wiener (1948) emphasized the accurate reproduction of a signal as the separation that distinguishes cybernetics from the laws of thermodynamics. And later, he stated that “the study of messages, and in particular effective messages of control, constitutes the science of Cybernetics,” (Wiener 1950, pp. 8–9). These principles of feedback control have now applicability in a wide variety of disciplines (e.g., communication, biology, industry, technology, and city). Generally, feedback is a recursive process that indicates that a system is operating so its actions can be scanned by sensory receptors (as a subsystem) as one state in its cycle of operation. In doing so, the system can, through the sensory receptors that collect information at low energy levels, monitor its performance, self-regulate, correct for deviations and changing conditions, steers its behavior, and adjusts its goals, to reiterate.

Further, the collected information can be encoded and made available for the operation of the system as part of the next input it receives for further stages of the system's performance. This allows the system to alter its output through regulating, correcting, steering, or modifying its future behavior in relation to its pre-encoded goals for better performance. This description of feedback in cybernetic paradigm is employed by Shannon and Weaver's in the theory of communication, in which the pivotal concept is codification (i.e., the transformation of perceived events into information) (Shannon and Weaver 1964). Based on the theory of cybernetics, two forms of feedback are recognized, negative and positive. Negative feedback occurs when negative messages are reported back to the systems central regulatory apparatus, and signals that no change or alteration in the system's goal is necessary (absence of deviation or any perceived mismatch between the system's actual behavior and its targeted goal). In contrast, when the system perceives a message of having a mismatch between its actual behavior and its targeted goal, positive feedback initiates modifications in the system's operation until the system is back on track to its goal.

Compared to Norbert Wiener, Bertalanffy as systems theorist adopted cybernetic principles with firm reservations as he, unlike Norbert Wiener who advocated the application of cybernetics on general systems, stated that cybernetic systems are "closed" with respect to the exchange of matter with the environment, but open only to information. von Bertalanffy (1968b, pp. 42–43) argues therefore that the cybernetic model does not provide for an essential characteristic of living organisms whose components are continually destroyed in catabolic and replaced in anabolic processes with corollaries, such as development, differentiation, and growth; and that regulative behavior in the feedback model is too structural and mechanistic. He contends that, as Wiener does, the cybernetic model introduced circular causality by way of the feedback loop, which accounts for the self-regulation, goal directness, and so on of the system; however, his view is that the feedback model is only one type of self-regulating system, and is too mechanistic in the sense that it presupposes structural arrangements (e.g., receptors, control center, and actuators). In line with Wiener, Bertalanffy claims that the concept of general systems is broader and non-mechanistic in that regulative behavior is not determined by structural conditions, but a dynamic interaction between many variables. Bertalanffy intended to make a point when he objected to cybernetic model as applied to living systems. In this regard, his objections are echoed in the criticisms leveled at employing a cybernetic model in the social and behavioral sciences. They were associated with the confusion surrounding the distinction between matter and energy, on the one hand, and information, on the other. In contrast, Wiener with Rosenblueth and Bigelow (1943) clearly acknowledge the distinctions between animal and machine. To put it differently, by his objections, Bertalanffy as a conscientious pioneer of scientific thought was concerned with avoiding overly ambitious applications of both systems analysis and cybernetics (von Bertalanffy 1968c). Generally, natural systems adjust their behavior so as to minimize deviations between their perceptions—the input from the external environment and their internal requirements encoded in a control center so to maintain a steady state of the internal operation of the system through feedback loops that ensure the self-stabilizing and self-corrective functions. The focus for Wiener was on the study of effective messages of control as constituting the science of cybernetics because he assumed that self-regulating systems tend toward entropy. Most commonly, a cybernetic focuses on process and behavior, dynamic, circular causality; the mutual causal loops of feedback cycles; interaction between multiple variables; and emergent morphogenesis. This implies that it is not the characteristics of the parts alone that are basic to any whole; rather it is the manner in which the system's components interact and interrelate that gives them their distinguishing properties.

The cybernetic model, when applied to a system, is determined by the form and the means of interaction between the components of that system and the outside environment. It involves different operational aspects in the process of control mechanism (self-regulation, self-correction, self-stabilization, and performance monitoring, etc.). The feedback loop cycles could be of a dynamic, circular causality or mutual causality that occurs through interaction between multiple variables (visible, emergent and/or hidden). The data collected in the control centers can be of different forms, including energy, matter, and information. Some complex systems may involve all forms depending on the environmental measures and conditions, as well as the properties of other involved systems or their components in the interaction process. How the system components are differentiated gives them their distinctive properties and determines their goals, codes, and needs. Regardless of the form of information in the control center (computer, brain, receptors, and effectors, etc.), the feedback loops occur to perform what it has to be done for the integrity and stabilization of the inner components of the system, whether be it performance monitoring, correction for deviations or changing conditions, steering behaviors, or altering goals. And this determined by the type of the feedback of control (negative or positive) being reported back to control centers. All these forms, when spread through a given system, may lead to different responses and behaviors determined by the dynamics of the system's configuration that shapes the interaction process through which the feedback loops occur. In light of this, the cybernetic system may actively receive the effects and influences of external causes and behaviors through adjusting its variables or conditions to instigate an efficient interaction. Further to this point, there might be hidden or unperceived processes or variables that trigger or maintain the communication between the parts of the system or between the systems in the cybernetics model. Thus, when the system takes in the input, it is the relationship between the components that determine the mechanism of its interpretation in terms of the system's organization and its code (it depends on whether the interaction is a necessary condition or instructed).

As with other systems thinking concepts, cybernetics has applicability in a variety of disciplines and fields. In the context of smart sustainable cities, cybernetics is at the core of many information systems as part of their ICT infrastructure, in addition to other management, transport, communication, and traffic systems. Information systems are categorized into two types termed evidence of existence and presentation of information, which are associated with the purpose for which the information system can be used. The former type is concerned with the domain of documentation and retrieval of information used, for example, in database systems. The structure of the latter type is developed based on cybernetic concepts like isomorphic model in analogy to the system structure of communication technology (Shannon and Weaver's communication theory). To generally structure information systems of the type of evidence of existence, the following processes related to cybernetics are applied: source-channel-sink with input–output characteristics, reversible code, filter-type communication channel. Generally, cybernetic systems use the stochastic process of trial and error that aims at maintaining a steady state of a system interaction within changing environmental conditions, which can be applied to information systems. This application of cybernetics enables information systems to respond to the effects of their output and other alterations in their environment (e.g., electrical, electronic, mechanical, human, and energy systems). In the communication model used in information systems, the concept of closed-loop models that is a part of cybernetics is applied to initiate two-way communication in information systems. Shannon's information theory was designed to optimize the transfer of information through communication channels and the feedback mechanism used to engineering control systems (Heylighen 1993). The practical relevance of cybernetics concept is that communication channels between faraway locations become so flexible and direct in analogy to nerves that connect and control different parts of an organism (Heylighen 1993).

Most of the presently advanced computing systems (e.g., big data and context-aware applications) draw from ideas proposed by cybernetic scientists: neural networks, computational learning, artificial life, and HCI. These tools offer better ways to organize and represent information by supporting the user in building useful models in information systems. The domain of computing applications has grown quickly, especially information processing and transmitting tools that somehow increase the general purpose "intelligence" of the user, that is to say, the control the user has over information and communication (Heylighen 1993). Moreover, from a cybernetic perspective, the process by which a social system interacts (learning) with its environmental can be applied to identify the necessary components of an information system structure and arrangement that cultivate learning in relation to the entities that comprise smart sustainable cities and rely on the use of ICT in their organization.

6.8.5 System Interaction

According to Boulding (1956), the interaction of an "individual" of some kind with its environment is a phenomenon of almost universal significance for all disciplines. Individual refers to a system or its components and the process of interaction. Disciplines of quantum physics, biology, computing, sociology, social psychology, and anthropology study some kind of systems and their interaction. Electron, atom, molecule, cell, plant, animal, human, family, community, state, city, company, university, and so on are considered individuals that exhibit behavior, action, or change, which is related in some way to the environment in which the individual (system or subsystem) comes into contact or into some relationship with other individuals (Boulding 1995). Generally, each individual consists of a structure or complex of individuals (subsystems) of the order immediately below it. For example, atoms are comprised of protons and electrons, molecules of atoms, cells of molecules, animals and humans of cells, social organizations of humans, and cities of citizens. Boulding (1995) argues that the behavior of each individual is explained by the structure of the lower individuals of which it is composed, or by certain principles of equilibrium or homeostasis according to which certain states of the individual are preferred. This behavior, action, or change emerges depending on the conditions of the environment in which the individual's dynamic interaction occurs, involving a wide variety of variables coming into a sort of connection or communication. In system interaction, Boulding (1956) focuses more on the concept of individuals interacting with each other in an environment in which the behavior or change is manifested from a system or subsystem.

From a conceptually different angle, Walonick (1993) contends that communication and transaction are the only intersystem interactions. He points that communication takes place through the exchange of information, while transaction involves the exchange of matter–energy as it is with open systems and the exchange of only energy as it is with closed system. Based on the law of physics, a closed system is one where interactions occur only among its inner parts and exchanges only energy with the outside environment in the interaction process, while an open system receives input in the form of energy, work, or matter from the environment and releases output to it; it is usually characterized by the dynamic interaction between its parts or with other systems, to reiterate. This approach to interaction has applicability in organizational, social, and urban environments in which communication and/or transaction can be manifested in many forms and at different levels. The sort of interaction in an organization may be cross-divisional, intra-departmental, inter-organizational, cross-cultural, or inter-stakeholders. The sort of interaction in a city may be cross-sectoral, intra-departmental, cross-districts, cross-industry, or inter-entities.

von Bertalanffy (1968a) proposes that a system is characterized by the interactions of its components and the nonlinearity of those interactions. Generally, dynamic interactions between systems manifest in the difference in the behavior of their parts when isolated or in a higher configuration. System interaction is a key concept developed to explain observable world phenomena. Noticeably, understanding behaviors or changes occurring through the dynamic interaction of different variables in a certain environment helps figure out what a system is about and how it contributes to that environment, irrespective of its particular properties and the elements involved. System interaction involves how simple and complex systems interact within defined or undefined boundaries. Such interaction occurs as the systems are open to each other to exchange resources through some kind of communication and/or transaction, depending on the type of systems involved in the interaction process (e.g., cells and bodies, humans and computers, organizations and markets, transport and traffic systems and mobility, and energy systems and the environment). The structure and arrangement of a system determine its distinctive properties in the case of a hierarchical order like molecules and cells, cells and humans, or humans and social organization. Moreover, the interaction may take only the form of communication through receiving and sending information, or only the form of transaction through receiving energy, work, and material, both in a dynamic fashion.

The applicability of the concept of system interaction is wide in such diverse disciplines and fields as physics, biology, computing, cognitive and social psychology, sociology, ecology, engineering, environmental sciences, and urban metabolism. System interaction is at the heart of the systems and subsystems of smart sustainable cities, including infrastructures, facilities, ecosystems, physical systems, and governance systems as well as the associated information, technological, organizational, operational, functional, social, environmental, and economic subsystems as to their interaction with urban systems. For example, in the context of HCI as part of information systems deployed across smart sustainable cities, system interaction involves human systems (a wide variety of human users like citizens, administrators, engineers, planners, architects, ICT experts, data scientists, and other professionals and practitioners) and computer systems (big data and context-aware applications intended for multiple uses). In addition, HCI focuses on how to implement the software and hardware mechanisms through merging them together through a set of sophisticated and intelligent interfaces that allow and support the interaction process between human users and computer systems. HCI is concerned with the study of major phenomena surrounding interactive computer systems and their design, evaluation, and implementation for human use within a variety of social, organizational, and urban settings. Most commonly, this interaction occurs through interfaces of various types and levels of complexity and granularity designed to establish connection for exchanging information through communication models. This interaction process involves both software (operating systems and communication programs) and hardware (general-purpose computer peripherals and electronic components). From a computer standpoint, there are many techniques in the field applied to computer design and graphics, operating systems, programming languages, in addition to engineering and design methods. Also, from a human viewpoint, the applicability involves communication theory, linguistics, social sciences, behavioral science, and cognitive psychology. The aim of HCI is to improve the interaction between human users and computer systems by making computers useful, effective, and receptive to different classes of users and to their needs in relation to diverse settings. Especially, information systems associated with big data analytics and context-aware computing are increasingly pervading smart sustainable cities, becoming the dominant mode of information and service delivery across all urban domains in the context of sustainability.

With more advanced knowledge to be acquired from the further study of system interaction, humans can create new ways of interaction and novel classes of interactive applications, including and developing new techniques, processes, and methods for designing more intelligent, effective, and efficient interfaces in attempts to respond to unmet needs and to deal with complex issues associated with the increasing manipulation, utilization, and application of the evolving big data and context-aware applications in the context of smart sustainable cities of the future that are intended to serve many purposes pertaining to different dimensions of sustainability across diverse urban domains and sub-domains. Indeed, one of the goals of HCI is to continuously improve methods for implementing interfaces and techniques for evaluating and comparing interfaces. HCI seeks to design systems to further curtail the difficulties and minimize the barriers between the human cognitive processes and the usefulness and responsiveness of computer systems to the needs of the different classes of users. Professional and practitioners in HCI are more often concerned with the practical application of design methods to real-world situations, such as graphical user interfaces, multimodal user interfaces, ambient interfaces, and web interfaces. These technical and computational capabilities are all based on the concept of system interaction.

6.9 Complexity Science in the Context of Smart Sustainable Cities

6.9.1 Complex Systems Simulation: Challenges and Driving Forces

There is a rapidly growing interest in complexity science within research on complex systems simulation, including in the area of smart sustainable cities of the future (see, e.g., Batty et al. 2012; Bettencourt 2014; Bibri and Krogstie 2017a, b). Complex systems simulation tackles some of the most challenging and fundamental questions of science, technology, and engineering related to many diverse disciplinary and interdisciplinary fields, including cities as social organizations. Issues of complexity are at the core of some of the major physical, spatial, environmental, social, technological, and economic challenges pertaining to smart sustainable cities. Complexity science is crucial to explaining smart sustainable cities as complex systems. And its increasing prominence in urban planning and development lies in that cities and related ICT networks and infrastructures present some of the most pressing real-world challenges for city governments and industries—in population growth, energy and environment, technology, economics, public health, transport, mobility, and so on. In particular, complexity science is rapidly gaining momentum due predominantly to new challenges and demands in technology. This is predicated on the assumption that there is increasing awareness that traditional approaches to design and engineering are failing to keep up with the increasing scale and connectivity of systems nowadays. Due to the management, design, and modeling problems facing modern ICT in the context of smart sustainable cities, practitioners and experts are critically concerned with ensuring efficiency, effectiveness, reliability, robustness, security, scalability, and evolvability in the interconnected ICT systems upon which modern cities increasingly rely. Systems from data storage and retrieval, to data processing and management, to telecommunications are rapidly increasing in scale. Also, processes and transactions in cities are becoming automatic, and many systems are being connected together. Automation and information intelligence are ushering in nearly all urban functions, thereby computer control increasingly being merged with human actions (Bibri and Krogstie 2017a). The big data provided from these functions offer "the prospect of a world in which the implications of how the city is functioning is continuously available and such immediacy is compressing time scales in such a way that longer term planning itself faces the prospect of becoming continuous as data is updated in real time"; and "the prospect of developing intelligence and planning functions at the same time as the very object that we are concerned with the city is changing its nature due to similar if not the same functions being used in its operation. This kind of space-time convergence in cities implies a level of complexity that only the new and powerful science of the kind that we will pioneer in *future ICT* can address." (Batty et al. 2012, p. 497) The increases in scale and connectivity of technological systems associated with smart sustainable cities make managing their complex dynamics more difficult. New approaches to design, engineering, management, and control seek to remove complex dynamical behaviors and emergent phenomena that are difficult to control and manage through minimizing errors and undesired behavioral patterns and thereby preventing the system from failing or crashing down. Such approaches to handling complex systems are urgently needed. This produces a strategic collaboration between industry and academia in that industry is required to drive new research at universities and seek relevant engineers and scientists trained to understand and deal with complexity. Accordingly, the knowledge associated with complex systems simulation are highly desirable and increasingly gaining central importance across many urban domains as part of urban sustainability and industry. Engineers and scientists trained in systems thinking and techniques for handling and exploiting the properties of complex systems are desperately needed. Moreover, one of the open challenges facing the researchers within the complex systems community is to overcome institutional obstacles to interdisciplinary and industrial involvement in complexity research. In addition, the availability of powerful computing power to simulate large-scale complex systems and investigate new ways of approaching their modeling and design is seen as another driving force in the recent upsurge of interest in complexity science. As to the latter, Batty et al. (2012, p. 485) point out that exploring many different kinds of models building on and extending complexity science is considered "important to build many different models of the same situation in the belief that a pluralistic approach is central to improved understanding of this complexity." Computational modeling allows new approaches that were not previously conceivable and testable. Formal mathematical methods and traditional design approaches remain inadequate to the design of large-scale systems that can handle complex dynamical behaviors, which are too difficult to forecast. The third main driver is the opportunities made available for complexity science to learn from biological systems in terms of gaining new insight into and inspiration for tackling complexity and gaining understanding of new approaches to modeling and controlling complexity in engineered and technological systems based on how biological systems work, and how they harness, exploit, and cope with emergent behaviors and processes and other systems-level phenomena. Complex systems exhibit emergent properties that are to be discovered and modeled. As our cities become an ever more interconnected places, a systems perspective becomes increasingly important. A central issue related to environmental sustainability is the emergent behavior of cities as complex systems.

6.9.2 New Prospects and Opportunities

In terms of where complexity science is headed, recent trends are bringing together research from a variety of established fields, including ICT, computing, mathematics, complex adaptive systems, systems biology, systems ecology, environmental sciences, systems engineering, physics, and management. This is to stimulate new research opportunities and thus create new research directions and innovative cross-disciplinary activities. Indeed, the push from academia and industry to solve complexity challenges pertaining to smart sustainable cities and other complex systems in a variety of fields has produced a massive response from the academic community and several research funding councils across the globe. One of the most exciting aspects of complexity science is its interdisciplinary and transdisciplinary nature. Of paramount to emphasize in this regard, is the interface of complexity science with organismic biology, cellular biology, and molecular biology, and ecology, in addition to many diverse disciplines. This involves fascinating possibilities to learn from how complex adaptive systems cope with emergent dynamical behaviors and adapt to control, harness, and exploit them in every possible way to be thought of. Indeed, a lot of research in complexity science spanning diverse domains, including smart sustainable cities, is seeking ways to model, understand, and extract the useful properties and behaviors of biological systems using big data analytics. This is with a prospect to better understand complex systems and to gain inspiration for new approaches into solving technological and engineering challenges associated with human systems in terms of efficiency, resiliency, control, optimization, management, and forecast. Among the systems from ICT that need new approaches inspired by biological systems to handling complexity in the context of smart sustainable cities include large-scale software development, data processing and management systems, database integration, sensor networks, infrastructure networks, semantic web, cloud computing, grid computing, wireless network reconfiguration, and telecommunication. This inspiration can emanate from many characteristic features of biological systems, including evolution dynamics, DNA and self-replication, metabolic networks, gene regulation networks, ecosystem sustainability, and immune systems and repair. The relevant topics that help connect the biological inspiration with the challenges pertaining to technological and engineered systems include, but are not limited to, the following:

Network science,
Dynamical systems,
Feedback control,
Machine learning,
Statistical theory of complex systems,
Information theory,
Evolutionary design and algorithms,
Self-organization and -regulation,
Simulation modeling,
Autonomic computing, and
Data mining and time series analysis.

In terms of complexity and network science, for example, complex systems can be represented by a network where nodes represent the components and links represent their interactions (Dorogovtsev and Mendes 2003; Newman 2010). Examples include ICT networks, infrastructure networks, urban networks, social networks, climate networks, biological networks, and neural networks. Networks as parts of complex systems can fail and recover spontaneously (see Majdandzic et al. (2013) for modeling this phenomenon). Interacting complex systems can be modeled as networks of networks (see, e.g., Majdandzic et al. (2016) and Gao et al. (2011) for their breakdown and recovery properties).

There is a general consensus that smart sustainable cities represent the crucible for ICT innovations and the best places where sustainable development can be made with invention, brilliance, and application. One of the reasons why many governments are embracing the idea of smart sustainable cities is that there is now a widespread view that to become and remain sustainable and be ahead of the game, cities must mobilize advanced ICT and what it entails in terms of big data analytics and related intelligence functions and simulation models to become ever smarter in the pursuit of their sustainable advantages or in realizing their full potential in terms of sustainability in an increasingly urbanized and computerized word. Indeed, the idea of cities growing ever bigger in terms of their populations and knowledge (i.e., sustainability, ICT, complexity science) epitomizes smart sustainable cities. The key to a more sustainable world is held by ICT, and this will be most clearly demonstrated in large cities. First and foremost, ICT of the new wave of computing is founded on the application of complexity science to urban systems, which are in and of themselves becoming ever more complex considering the challenges of sustainability and urbanization. This is due to the invention and application of new modes of human functioning in cities using advanced ICT.

The notion of smart sustainable cities is at the forefront of understanding complex social and economic systems (or organizations) using the very human engineered ICT systems that are fashioning those systems in the first place. Smart sustainable cities, which adopt ICT in its various forms (systems, platforms, architectures, infrastructures, data analytics, networks, applications, services, etc.), change the very nature of the process of adopting ICT by means of that same ICT. As mentioned above, the problems that we deal with, which pertain to all cities, are wicked and intractable problems as known many years ago (e.g., Rittel 1969; Rittel and Webber 1973). The great innovation of ICT of the new wave of computing lies in that any problem should be approached in full knowledge of the dilemma that tackling wicked problems may render them worse due to the unanticipated effects which were ignored or due to the unforeseen consequences which were difficult to identify as risks because the systems in question were handled in too simplistic terms. This includes the concerns for privacy and security and the risks involved in the generation of new routinized data across urban domains in relation to sustainability initiatives when using and applying advanced ICT in smart sustainable cities. Whatever approach we adopt should be built on the idea that the nexus is complex and we should not overlook this interwoven complexity at our uncertainty and peril.

It is important to put more emphasis on questions involving organization that imply software development, database administration, and management of large-scale computer resources, networks, and data, in spite of the fact that smart sustainable cities as programs and initiatives would be strongly focused on hardware in terms of infrastructures and networks. Here much of complexity science comes into play in terms of the aforementioned relevant topics that help connect the biological inspiration with the challenges pertaining to technological and engineering systems. This pertains mainly to urban intelligence functions and urban simulation models in terms of integration of data, patterns, models, and methods using advanced ICT. This involves a constellation of issues in ICT that surround the use and development of new varieties of computation entailing data sensing, data acquisition, data storage, database coupling, data mining, data coordination, and so on. These aspects will be part of new governance structures for new intelligence functions in the context of smart sustainable cities that utilize real-time construction and use of a variety of simulation models and optimization approaches relevant to decision support pertaining to sustainability, coupled with much wider participation in decision-making (see Batty et al. 2012). In this respect, city governments are challenged to find effective ways of governance to manage new complexities as urban systems and domains become more network-centric and intricate to ensure flexibility and resiliency.

6.9.3 A New Class of Urban Simulation Models in Light of Complexity Science

6.9.3.1 Incorporation of Dynamical Properties and Related Challenges

One of the major themes under debate in academic circles is to provide portfolios of urban simulation models which can inform the design and planning of smart sustainable cities of the future, and to construct new forms of such models while exploring many different kinds of modeling and simulation approaches and extending the science of complexity. A new class of powerful simulation models is in urgent need that can embrace the emerging forms of complexity characterizing the complex phenomenon of smart sustainable cities as a set of interrelated systems and domains, as well as the coupling, coordination, and integration of these. Simulation analyses are to be conducted in support of urban design and planning (see, e.g., Batty et al. 2012; Bibri 2018; Bibri and Krogstie 2017b) in the pursuit of optimal solutions for advancing the contribution of smart sustainable cities to the goals of sustainable development. In this regard, simulations serve to enhance the functionality of decision support systems pertaining to urban operational functioning by adding the dynamic element, and to allow to compute estimates and predictions, including optimization and what–if analyses. In addition, simulation can be applied for the development and testing of large–scale systems (energy, transport, traffic, etc.) in early phases. In particular, simulation models can simulate urban dynamics as self−organizing evolution processes pertaining to sustainability under selective pressures through balancing between selection mechanisms and innovation patterns. Especially, there is a need for city models that can handle current planning conceptions and address emerging challenges in an increasingly urbanized and computerized urban world—pervaded with computer technology and dominated by flows of computable information that leaves no physical traces and has no spatial facets like area, position, location, and shape (Bibri and Krogstie 2017a). Hence, the real challenge is to build simulation models that grapple with these shifts and that have the potential to embrace new conceptions of the way smart sustainable cities operate and function. We need to build simulation models that take into account the changing and evolving aspects of smart sustainable cities as complex systems, including how the planning and decision processes might change overtime, especially the real–time city and its sensing is getting closer to providing information about longer term changes in terms of operational functioning. Indeed, as stated by Batty et al. 2012, p. 507), "Spatial scales and time scales are being collapsed by the emergence of real-time data from the bottom up. Data sets are being created that show immediately the functioning of the real-time city but also imply how long term changes in the city can be detected. In short, if all the data that we collected were in real time, at any instant, we could aggregate the data to deal with change in the city at any scale and over any time period. This prospect is a long way off and will never be reached (for once we reach it we will find more and different data that need to be collected) but what it does promise is an ability to have a real-time view of change at different spatial scales and over different time scales." In fact, in terms of the human capacity to predict the behavior of complex systems through modeling, it is believed that the sciences of complex phenomena could not be modeled after the sciences that deal with essentially simple phenomena. This relates particularly to chaotic systems whose long-term behavior remains difficult to forecast with any accuracy. Nonetheless, one can theoretically make accurate predictions about the future of smart sustainable cities as complex systems on the basis of the kind of knowledge that is as good as it is possible of the relevant equations describing their behavior. This is unfeasible in practice at the current stage of research into complexity science and its application. Prigogine (1997) argues that complexity gives no way whatsoever to precisely predict the future, and is non-deterministic. Hayek (1978) notably explains that complex phenomena can only allow pattern predictions using modeling approaches, compared with the precise predictions pertaining to non-complex phenomena. Regardless, many real complex systems, including cities, have the potential for radical qualitative change while retaining systemic integrity.

In the context of smart sustainable cities, the use of computer simulation is primarily intended to stimulate research in the simulation of the adaptive behavior of smart sustainable cities due to the underlying web of ongoing, reciprocal relationships, which cycle to generate the patterns of behavior that are to be exhibited as a result of the interaction between physical system, economic system, social system, and environmental system as nested systems and networks of networks. Simulations pertain to equations characterizing the nature of reciprocal relationships and their direction and strength, and then to the simulation of the system behavior on a computer. This necessitates in this context ensuring that the set of reciprocal relationships involved produce the patterns of behavior that are to be exhibited by smart sustainable cities. Important to consider additionally are the mechanisms believed that such cities can use to control themselves. The basic idea is to explore how things are related to each other and how they are connected to, configured in, and constrained by the diverse systems forming smart sustainable cities in terms of pressures, constraints, and expectations. The ultimate aim is to design, manage, and build control systems of technological and engineering systems associated with smart sustainable cities in such that they can proliferate and increase in size and connectivity in line with population growth, environmental pressures, changes in socio–economic needs, and economic intensity.

The behavior of smart sustainable cities as complex systems is intrinsically difficult to model due to the dependencies, relationships, or interactions between their subsystems or between them and the environment. Such cities have distinct dynamical properties that arise from these relationships. The commonalities among complex systems as they appear in a wide variety of fields, including city-related disciplines, have become the topic of their own independent area of research. A deep level of understanding of the dynamical properties of complex systems is crucial to drastically changing both the urban simulation models that we are able to build based on the analysis of big data of various velocities (especially real-time data) and the way in which the underlying technologies can inform the planning and decision process with simulations and decision support. Constructing dynamic models of smart sustainable cities functioning in real time from routinely sensed data as well as related simulation models, thanks to the ability of sensing technologies to provide information about longer term changes, implies that such cities could develop intelligence functions in the form of innovation laboratories that enable urban monitoring and planning and inform future designs (Batty et al. 2012; Bibri and Krogstie 2017a, b). The dynamical properties of complex systems are at the core of these two conceptions of how smart sustainable cities can function and be designed. Specifically, as a set of interacting systems, smart sustainable cities must be designed and built to be scalable, robust, and adaptive by incorporating such dynamical properties as self-organization, self-adaptation, self-regulation, feedback loops, self-repair, spontaneous order, nonlinearity, and evolution, thereby, ideally, mimicking biological systems.

Besides, the study of smart sustainable cities as complex systems should regard their collective, or system wide, behavior as the fundamental object of study when it comes to their planning and development. This involves going beyond the limits of existing technological and engineering systems which are merely complicated to involve how to harness and exploit dynamical properties associated with their behavior. This is at the heart of joined-up planning which entails integration across the board, under some form of selective pressures and sensitive reactions, that enables system-wide or collective effects to be monitored, tracked, understood, analyzed, and built into the very designs and responses characteristic to the operations, functions, and strategies pertaining to the behavior of smart sustainable cities (see Batty et al. 2012). This presumes focusing on the usual components that make such cities function as a social organism. The idea of ICT penetrating wherever it can to enhance sustainability performance in the form of big data analytics, intelligence functions, and simulation models is central to this quest. This entails incorporating ICT in all urban domains and planning levels (e.g., the built environment, mobility, traffic, energy, transport, urban design, land use, transport planning, environmental planning, metropolitan planning, regional planning, national planning, and local planning). In all, what is crucially important in the quest for making smart sustainable cities function as a social organism or biological system is a deeper and broader understanding of the main concepts of complex systems and their effective incorporation in the very design, engineering, and modeling of technological systems associated with the operating and organizing processes of urban life. Especially, complexity science brings together deep scientific questions pertaining to sustainability and urbanization with application-driven goals across the field of smart sustainable cities. These concepts include, but are not limited to, systems, complexity, networks, nonlinearity, emergence, adaptation, and spontaneous order and self-organization. They are described below, following general complex systems theory.

6.9.3.2 Systems Concepts

Systems

Systems concepts play a central role in complex systems due to their interdisciplinary applicability. An adequate description and discussion of (complex) systems has already been provided in Sect. 6.2. To add to this account, a system is a set of entities determined by its boundary that form a unified whole. This is manifest in its interactions, relationships, or dependencies in terms of its components. Any entities lying outside the system become part of its environment. A system has parts that exhibit properties and behaviors which are distinct from what it itself can exhibit as system-wide properties that generate collective behaviors. This is characteristic of how its parts behave or how the system interacts with its environment. Hence, the processes that take place over time as part of the notion of behavior are at the core of the study of systems.

Complexity

Due to the multifarious nature of the concept of complexity, there are many archetypal examples of complexity, including chaotic behavior, emergent properties, and computational intractability of modeling. In particular, systems exhibit complexity when regularly found conditions are involved in difficulties with modeling them due to the number of parameters involved that grows too rapidly proportional to the size of the system and the nature of the connectively of its parts. This implies that their properties which produce behaviors cannot be understood apart from the very relationship between their properties and behaviors (which almost entirely govern them due to their properties) that make them difficult to model. In this regard, any kind of models generated on the basis of modeling approaches that overlook such difficulties become inaccurate and of less value. Like in many areas, researchers in smart sustainable cities (e.g., Batty et al. 2012) are attempting to solve these systems as part of urban development, since as yet no fully general theory of complex systems has thus far evolved to address and overcome these issues. The way forward in this endeavor is that urban researchers view the main task of modeling to be capturing the complexity of smart sustainable cities as their systems of interest. This also applies to particular domains such as mobility (Giannotti et al. 2011).

Emergence

Another common concept and aspect of complex systems is the presence of emergent properties and behaviors, which result from the relationships, interactions, or dependencies they form by virtue of being within a system, and are not apparent from their components in isolation. Emergence is associated with the appearance of such properties and behaviors. It is of high applicability in smart sustainable cities as a field of study. In this regard, it denotes the appearance of unplanned organized behavior (order) pertaining to environmental and socioeconomic changes due to urbanization and new economic and social properties and behaviors associated with the unsustainability of the city. Denoting a breakdown of city organization as well, it describes urban phenomena which are difficult to forecast from the smaller entities (e.g., urban domains) that make up the city.

Networks

Network is a core concept of complex systems due to their inherent interacting components. It represents a web of relationships between their components, usually depicted as nodes illustrating the components and links illustrating their interactions, or as a graph of vertices connected by edges. In the context of smart sustainable cities, networks can describe the relationships between constituent entities within a city organization. Networks describe the sources of complexity in such cities as large networks or networks of networks. The number of relationships between the entities of such cities can quickly dwarf that of entities in the network as it grows. One way of depicting smart sustainable cities is through viewing them as constellations of instruments across many spatial scales that are connected through wirelessly ad-hoc and mobile networks with a modicum of intelligence, which provide and coordinate continuous data on different features of urban domains (activities, processes, citizens, and entities) in terms of the flow of decisions about the physical, infrastructural, operational, functional, and socioeconomic forms of such cities. Studying cities as networks thus enables many useful applications of network science.

Nonlinearity

Characteristic to complex systems is the notion that a small perturbation may cause, due to the nonlinear nature of the relationships between the parts of a system, a large effect (e.g., chaos, butterfly effect) or a proportional effect. This relates to their nonlinear behavior caused by reciprocal relationships over time based on feedback loops, time delays, flows, and stocks. Accordingly, cities as complex systems may respond in varying ways to the same input (e.g., energy consumption) depending on their context. Speaking of context (the current state of a city or its parameter values), a change in the size of the input received by a given city in the form of energy does not produce a proportional change in the size of the output pertaining to the environment. In other words, a given change in input may generate significantly greater than or less than a proportional change in output. Further, some nonlinear dynamical systems may be associated with chaotic behavior, which is sensitively dependent on initial conditions that a complex system can exhibit, as discussed earlier. Here small changes to initial conditions can lead to drastic results, thereby the difficulty in, if not impossibility of, modeling the chaotic behavior of complex systems numerically. In addition, after a complex system returns to its original state, it may behave in a completely different way in response to exactly the same event. Thus, the chaotic behavior of complex systems poses significant challenges when it comes to extrapolating from past behaviors as part of a system's experience.

Spontaneous Order and Self-organization

Spontaneous order is the emergence of unplanned order or organized behavior out of seeming chaos in the social sciences. It is also named self-organization in the hard (physical) sciences. Central to spontaneous order is that the actions of a group of individual elements of a system are coordinated without centralized planning. Thus, spontaneous orders are created and controlled by no one. It results from human actions, not from human design (Hayek 1978). However, both concepts are of applicability to smart sustainable cities due to the kinds of systems they involve, including physical, economic, and social systems, and how these systems interact with their environment. Regarding spontaneous order, for example, a particular social or economic order in a city may, for example, emerge from a combination of self-interested individuals or entities that have no intention to create order through planning. As to self-organization, it is associated with environmental changes triggered by a particular pattern of energy consumption due to the intensity of economic and social activities. Examples of systems which have evolved through spontaneous order include ecosystem, language, the Internet, a stock market, the evolution of life on Earth, and the universe. In contrast to organizations which are characterized by hierarchical networks, spontaneous orders are differentiated by being scale-free networks, but organizations often constitute an integral part of spontaneous social orders.

Adaptation

The adaptive behavior of complex systems is about having the capacity to change and learn from experience. This feature relates to complex adaptive systems, which represent special cases of complex systems. Examples of complex adaptive systems are the ecosystem, the biosphere, the city, and any social group-based endeavor in a socio-cultural system such as sustainable communities and ecological districts. Adaptation involves dynamic evolutionary processes and has a functional role in each organism in terms of sustaining itself and evolving by natural selection. Cities face a succession of environmental challenges as they evolve, and show adaptive behavior in response to the imposed conditions by using technological and engineering solutions or integrating technological systems with the design concepts and planning principles of sustainable urban forms. This gives them resilience to varying environmental conditions.

6.10 The Role of Big Data Analytics in Disentangling Intractable Problems

The interlinked global shifts in urbanization, sustainability, and ICT have converged under smart sustainable cities as a new holistic approach to urban development to deal with and overcome the kind of complex challenges and intractable problems facing modern cities. New circumstances require new responses. This entails exploiting the potential of ICT as an enabling, integrative, and constitutive technology for solving the environmental, social, and economic problems of sustainability due to the underlying transformational, substantive, and disruptive effects of ICT (Bibri and Krogstie 2016, 2017a, b). As an advanced form of ICT, big data analytics provides a very rich nexus of possibilities in terms of overcoming the timeless challenges of governments and disentangling the mounting problems of unimaginably urbanized areas thanks to the associated powerful engineering solutions and novel applications (see Chaps. 5 and 8 for further details). There has been much enthusiasm about the immense opportunities provided by new and more extensive sources of urban data to better operate, manage, plan, and develop cities to improve their contribution to the goals of sustainable development. Cities as complex systems, with their domains becoming more and more interconnected and their processes highly dynamic, rely more and more on sophisticated technologies to realize their potential for responding to the challenges of sustainability and urbanization.

The problems of smart sustainable cities are primarily about citizens. Environmental, economic, and social (and sometimes infrastructural and physical) issues in contemporary cities define what planners call "wicked problems" (Rittel and Webber 1973), a term that has gained currency in urban planning and policy analysis, especially after the inception of sustainable development in the early 1990s. These kinds of problems are not expected to yield to engineering solutions for specific reasons (Rittel and Webber 1973) that break the assumptions of feedback control theory (Astrom and Murray 2008). Bettencourt (2014) addresses the issue of wicked problems in light of computational complexity theory, drawing on More and Mertens (2011), to formally argue that comprehensive or detailed urban planning is computationally intractable. This signifies that solutions entailing the knowledge and prediction of chains of detailed behaviors in smart sustainable cities as complex systems have the basic property that they become practically impossible, irrespective of the scale and diversity of data available. This "clarifies the central dilemma of urban planning and policy: planning is clearly necessary to address long-term issues that span the city…and yet the effects of such plans are impossible to evaluate a priori in detail" (Bettencourt 2014, p. 13), although they are informed by established knowledge and solid theoretical foundations (e.g., sustainability science, systems science, complexity science). The urban world is constantly changing, intrinsically unpredictable, and infinitely rich.

Based on the above reasoning, there is no perfect solution to urban sustainability problems in terms of planning and design, and each set of identified solutions would contain strengths and weaknesses. The difficulty in formulating the right solutions to wicked/ill-structured problems encountered by urban planners and administrators lies in the chaotic nature of multiple cause and effect relationships and the way they shape the patterns of behavior of cities. In other words, wicked problems, when tackled, "became worse not better due to the unforeseen consequences and unanticipated effects which were ignored because the systems in question were treated in too immediate and simplistic terms." (Batty et al. 2012, p. 506) In view of that, sustainable urban planning and design is required to examine problems from different angles and find the best possible solutions. In this regard, "relatively simple-minded solutions, enabled by precise measurements and prompt responses, can sometimes operate wonders even in seemingly very complex systems where traditional policies or technologies have failed in the past." (Bettencourt 2014, p. 14). To put it differently, relatively simple solutions with no great intelligence involved can, under specific circumstances, solve very challenging problems. One manifestation of this has to do with using fast and precise enough measurement and adequate simple reactions instead of applying smart approaches. This is the logic of feedback control theory as part of modern engineering (Astrom and Murray 2008). In view of that, knowing the desired operating point for a system and having the means to operate on the system, while observing its state change via feedback loops, can enable to turn it into a simple problem under general, crucial conditions that can measure and recognize potential problems, just as they start to arise and act to make the necessary corrections (Bettencourt 2014). In this context, the crucial issue is that of temporal scales, which are at the core of urban big data and their use in urban planning in terms of short-term thinking about how smart sustainable cities can function and be managed; every urban system has intrinsic timescales at which problems develop—minutes, hours, days, and decades. Cycles of measurement and reaction must act well within this window of opportunity to avoid such complex problems by simple means (Bettencourt 2014).

It is conspicuous now that the emergence of urban big data may offer radically novel solutions to difficult urban sustainability problems. Modern ICT is now so fast in comparison to most physical, environmental, social, and economic phenomena that myriads of important urban planning and policy problems are falling within this window of opportunity (see Bettencourt 2014). In such circumstances, models of system response enabled by big data analytics (see Chap. 4 for a discussion of deployed data mining results as part of diverse solutions to urban sustainability problems) can be very simple and crude and typically be linearized (see Astrom and Murray 2008). Thus, the analytical engineering approach conveniently bypasses the complexities that can arise in the systems of smart sustainable cities at longer temporal or larger spatial scales. The potential miracle of big data in such cities lies in essentially solving difficult and important urban sustainability problems without theory. Many examples of urban planning, management, and policy in smart sustainable cities that use data successfully can have this flavor, irrespective of whether their implementation involve organizations or computer algorithms.

Big data analytics utilizes complex computational processes in analyzing urban phenomena and planning urban systems. The core enabling technologies underlying big data analytics allow for gathering, processing, and analyzing various kinds of urban data on several urban systems and domains across different spatial scales and over different time spans. However, in the quest to master the complexity of the process of extracting or discovering knowledge from or in large masses of data in the context of smart sustainable cities, it is necessary to develop an entirely new holistic system that integrates data collection, mining, querying, and visualization. The entire processes of data mining and knowledge discovery in databases (see Chap. 4 for an overview) able to create the needed knowledge for enhanced decision-making and insights as services associated with different dimensions of sustainability should be expressible within applications across diverse urban domains that support the different phases of the respective processes (see Chap. 4 for a detailed account). A preliminary, partial example of this line of research already exists in the domain of mobility (e.g., Giannotti and Pedreschi 1998) in relation to smart cities of the future (e.g., Batty et al. 2012). This is also of relevance to smart sustainable cities of the future (Bibri and Krogstie 2017b). The domain of mobility is increasingly becoming an exemplar for encompassing all the domains of such cities (e.g., traffic, transport, energy, land use, health care, education, network performance, and environment) in terms of data, patterns, models, and simulations as well as their amalgamation in the context of sustainability. This is a continuing research challenge for ICT of the new wave of computing (Bibri and Krogstie 2017b).

As big data analytics processes, data mining and knowledge discovery: the automated extraction and discovery of useful knowledge from and in large datasets, respectively, are associated with, in the context of smart sustainable cities, advancing their contribution to the goals of sustainable development through knowledge-driven or well-informed decision-making processes pertaining to diverse urban systems and domains. In more detail, these processes target optimization and intelligent decision support related to the control, optimization, management, and planning of urban systems as operating and organizing processes of urban life, as well as to the enhancement of the associated ecosystem and human services pertaining to utility, health care, education, safety, and so on. This occurs through the implementation of simulation models, optimization strategies, and decision-taking processes as part of urban intelligence functions. Additionally, these processes target the improvement of practices, strategies, and policies by changing them based on new trends and shifts. In all, the related analytical outcomes serve to improve urban operational functioning, optimize resources utilization, reduce environmental risks, and enhance the quality of life and well-being of citizens.

Accordingly, smart sustainable cities need to relate their typologies, infrastructures, ecosystem services, human services, and governance models to their operational functioning, planning, and development through monitoring, analysis, evaluation, modeling, simulation, prediction, and intelligent decision support based on big data analytics as a set of advanced technologies and their novel applications for optimization, control, automation, management, strategy development, and policy design in the context of sustainability. In this respect, the efforts should be directed toward demonstrating how developments in big data analytics and the underlying core enabling technologies (namely sensor networks, data processing platforms, cloud computing infrastructures, and wireless networks) can be integrated so to make smart sustainable cities intelligently more sustainable in the way urban planners, administrators, departments, and authorities can use new technological applications, services, and capabilities for improving sustainability and integrating its dimensions.

6.11 Sophisticated Approaches into Tackling Urban Sustainability Problems

6.11.1 Urban Intelligence Functions

To understand complex systems and the way they behave, form relationships with their environment, and evolve necessitates computationally and analytically sophisticated methods and powerful models. Smart sustainable cities are considered as complex and dynamically changing environments. Systems theory recognizes that the parts and most individual details of complex systems are irrelevant to describe them as a whole while identifying crucial general dynamics (Anderson 1972), e.g., a city exists, operates, and functions even as urbanites change their place and way of living. It follows that the complexity sciences (e.g., information theory, nonlinear dynamics, networks, pattern formation, collective behavior, emergence, adaptation and evolution, and systems theory) are integral to the understanding of cities in order to track the underlying changing dynamics and reciprocal relationships pertaining to the patterns of behavior they exhibit as complex systems. The purpose is to develop solutions that do not create further problems, and also to solve serious problems by focusing on external agents merely because they are embedded in larger systems. In the context of smart sustainable cities, such problems include pollution, toxic waste, environmental degradation, economic instability, social inequality, unemployment, urban isolation, and public health decrease. Smart sustainable cities are inherently intricate through the very technologies being used to not only understand them, but also to monitor and analyze the underlying physical structures, spatial and temporal scales, and operating and organizing processes in relation to management, planning, and development, with the purpose to overcome the challenges of sustainability and urbanization they are facing, in addition to being developed through a multitude of decisions from the bottom up to the top down (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri and Krogstie 2017a, b; Kramers et al. 2014; Shahrokni et al. 2015). Accordingly, embedding more and more ICT into smart sustainable cities will undoubtedly continue and even escalate for the sole purpose of providing the most suitable tools and methods for handling their complexity as systems and thus dealing with the problems they are facing and will continue to face. The underlying premise is that advanced ICT is founded on the application of the complexity sciences to urban systems and problems. As such, it has an instrumental and shaping role in not only improving the planning and development process of smart sustainable cities, but also in monitoring, understanding, and analyzing such cities through big data analytics and related urban intelligence functions and urban simulation models for making strategic decisions about their collective behavior and the dynamic relationship they form with their environment in the context of sustainability. These technologies constitute new conceptions of the way smart sustainable cities can perform as to their operational functioning, adaptation, and development as regards to their contribution to the goals of sustainable development.

Urban intelligence functions provide a new perspective as to how smart sustainable cities function and make use of the complexity sciences in fashioning powerful new forms of optimization strategies and simulation models that generate urban structures and forms that improve sustainability. The outcome of big data analytics associated with various urban domains and their integration (e.g., in terms of databases, processes, and activities) is of central importance to the development of urban intelligence functions for enhanced decision-making in relation to sustainability. As advanced forms of decision support, urban intelligence functions enable to monitor and plan smart sustainable cities in terms of the collective behavior of their subsystems as to operations, functions, strategies, designs, and practices. In more detail, developing urban intelligence functions allows to explore the idea of smart sustainable cities as techno-urban innovation labs (see, e.g., Batty et al. 2012; Bibri and Krogstie 2017a), where these intelligence functions can—based on the use of data science, computer science, and complexity sciences in developing advanced simulation models and optimization methods as well as in exploring many different kinds of modeling approaches (e.g., Batty et al. 2012; Bibri and Krogstie 2017a)—allow for monitoring and planning smart sustainable cities with respect to the following:

- The Efficiency of energy systems;
- The improvement of transport and communication systems;
- The effectiveness of distribution systems;
- The optimal use and accessibility of facilities;
- The efficiency of human service delivery; and
- The optimization of ecosystem service provision.

In this regard, such functions can take the form of centers for scientific research and innovation with the primary purpose of continuously improving the contribution of smart sustainable cities to sustainability thanks to the prospect of building models of real-time cities in terms of their functioning on the basis of sensor-based/machine generated data becoming clear and achievable. They relate to the idea of joined-up planning which entails "integration that enables system-wide effects to be tracked, understood, and built into the very responses…that characterize the operations and functions of the city" (Batty et al. 2012, p. 490). The kind of intelligence functions envisioned for smart sustainable cities of the future would be woven into the institutional direction with respect to promoting and advancing sustainability and generating and sustaining a better quality of life for citizens.

As regards to decision support as a form of urban intelligence, structures for decision support systems that involve the wide portfolio of models and tools pertaining to big data analytics techniques for the planning of smart sustainable cities are still in their infancy. With new advances in big data technologies, the process of building intelligence functions for smart sustainable cities as to city governments will shift from top to down (expert and professional organizations) to engaging citizens with experts due to the complexity associated with smart sustainable cities and related development endeavors. This entails integrating databases and models for supporting the development of this sort of integrated intelligence, with new or refashioned ways at different levels, including visualization of data and urban sustainability problems, using tools for informing and predicting the impacts of future sustainability scenarios, and engaging citizens and their useful and relevant recommendations, all into integrated systems that operate continuously and robustly. The development of these environments pertains to several different yet related kinds of sustainable urban planning problems across diverse urban domains as well as to various spatial and temporal scales. Thereby, the issues of multi-scale and multi-temporal modeling could be resolved on the basis of rudimentary ideas of integrated modeling (see Batty et al. 2012).

6.11.2 Urban Simulation Models

Serving to developing a deep level of understanding of complex systems, systems theory, and complexity science represent the study of the whole system as well as its parts and their mutual interactions where simulation models are the vehicle most often employed to describe and aid in explaining complex systems. This is of high relevance and applicability to smart sustainable cities as complex systems, in particular in relation to the investigation and evaluation of their contribution to the goals of sustainable development, as well as to what should be done to optimize and sustain this contribution.

As hinted at above, urban intelligence functions involve simulation models, which need to be constructed and diversified in relation to different urban domains and how their diverse constituents interrelate and can be coordinated internally and externally in the context of smart sustainable cities. Here the modeling and simulation process entails creating and analyzing digital prototypes of physical, infrastructural, environmental, socio–economic, spatiotemporal, operational, and functional models in terms of how they operate, interrelate, coordinate, and affect one another to identify and predict dynamic changes in the underlying behavioral patterns due to some kind of reciprocal relationships cycling to produce the kind of patterns that smart sustainable cities might exhibit as a result of their functioning, adaptation, and development in relation to sustainability. This allows to determine and forecast potential problems in the real world, and to look at more effective ways to overcome or eradicate them. In this regard and context, complex system modeling and simulation denotes the operation of the whole model of the system (smart sustainable city and its sub–systems) to evaluate the performance of the system behavior as regards to sustainability, and allows to adjust any parameters within the system under investigation and then to optimize the system to increase success in terms of enhancing different aspects of sustainability across various urban domains (Bibri and Krogstie 2017b). This involves alterations in such domains in terms of operations, functions, designs, services, strategies, and policies, as well as in how these domains interrelate and are coordinated.

There is an evolving immediacy in the building of all kinds of urban simulation models thanks to the recent advances in, and pervasiveness of, sensor technologies and their ability to provide information about medium- and long-term changes in the context of real-time cities (e.g., Bibri and Krogstie 2017a). This involves replacing aggregate models with disaggregate ones while exploring many different kinds of models construction and extending the complexity sciences and thereby diversifying the approach to the construction and evolution of these models (e.g., Batty et al. 2012; Bibri and Krogstie 2016, 2017b). It is important to construct many different models of the same urban situation, predicted on the assumption that as a pluralistic approach is central to improving the understanding of this complexity (Batty et al. 2012). The prominence of urban simulation models in this context lies in aiding urban planners, administrators, architects, and experts in understanding by means of evaluation procedures under what conditions and in what ways urban systems and domains fail to deliver at the level of some dimensions of sustainability and what to do about potentially predicted changes, emergent dynamics, or forecasted problems, e.g., whether there is a need to further enhance the integration and coupling of urban systems or some of their components, to further organize and coordinate urban domains, and/or to create better or merge hitherto unconnected typologies and design concepts across certain spatial scales. In short, the aim is to inform the future design and planning of sustainable cities on the basis of predictive insights and forecasting capabilities in ways that strategically assess and optimize their contribution to the goals of sustainable development.

Regarding the evolving smart sustainable urban planning approach (e.g., Bibri and Krogstie 2017a), most of the simulation models developed over the last 50 years or so to understand how cities function and predict their changes on different spatial scales and over various temporal intervals need to be advanced in ways that encompass the new shifts brought by sustainability and urbanization as new determining factors of modern cities as complex systems, as well as by new conceptions from systems dynamics: nonlinear behavior over time based on time delays and stocks. The latter pertains to short termism (see Chap. 5 for a relevant discussion) associated with urban thinking and planning increasingly enabled by big data analytics. "This kind of space-time convergence in cities implies a level of complexity that only the new and powerful science of the kind that we will pioneer in *future ICT* can address." (Batty et al. 2012, p. 497) In the history of urban planning, the focus of most applications has been on what happens in cities measured over years and decades (Batty 2013).

At present, the optimization achieved in some simulation models concerning urban operation research tend to be generally used in intuitive dialogue with policymakers within what is known as planning support systems (Brail 2008). However, one approach to advance urban simulation models is to integrate diverse and hitherto unconnected urban domains (e.g., transport, mobility, accessibility, land use, water management, waste management, energy, natural environment, built environment, public health, public safety, education, governance and citizen engagement, and science and innovation) on the basis of environmental and socioeconomic performance criteria, for example. Drawing on Batty et al. (2012) and Bibri and Krogstie (2017a), the focus in smart sustainable cities should be on evolving new urban simulation models for various urban domains associated with sustainability that pertain to new kinds of dynamic and real-time data in relation to the built, infrastructural, operational, and functional forms of smart sustainable cities across different spatial scales and over multiple time spans. These distributed, networked, integrated, mined, and modeled data can be linked to traditional movements and different aspects of spatial activities to inform urban intelligence functions as advanced forms of decision support pertaining to the environmental and socioeconomic performance of smart sustainable cities. This should be supported by novel methods for integrating and coordinating decision support strategies and systems. Crucially important to these emphases is that urban simulation models associated with sustainability in connection with different urban domains should be grounded in clear conceptions in terms of the way in which they can be employed and extended to inform the planning and design of smart sustainable cities on different spatial scales and over multiple time spans. In addition, as to models for using urban data across spatiotemporal scales, real-time data need to be merged with traditional data across different urban entities as sectional sources of data based on simulations that link real-time sustainability issues to long-term strategic sustainability planning (see Batty et al. 2012).

Underlying the idea of smart sustainable cities of the future is that the development and implementation of a new class of simulation models constructed based on big data analytics and supported by database integration and network coupling pertaining to various urban domains and sub-domains entails that these simulation models themselves will grow sophisticated and expend as urban structures and spatial organizations will evolve over time. This pertains to producing new patterns of behavior that such cities might exhibit due to reciprocal relationships as a result of new cycles pertaining to the interaction between the subsystems of such cities. This is anchored in the underlying assumption that simulation and prediction methods are built on top of the mined behavioral patterns and dynamically changing models associated with real-time cities. Agent-based models (Batty et al. 2012), which can emulate the dynamics of smart sustainable cities (traffic, mobility, transport, climate, energy, land use, etc.) as a result of urban activities, can be used to shape and inform collective decisions in an intelligent manner. The kinds of models needed most are those that grapple with the shift associated with our increasingly computerized and urbanized world, which is dominated by the flow and manipulation of information instead of material and energy. The rudiments of this kind of models are available in many of the agent-based models constructed for urban sectors (Pagliara et al. 2013). However, they still need to be further advanced in ways that render them more suitable and focused as to catalyzing and boosting the strategic process of sustainable development and thus advancing sustainability, thereby increasing their effectiveness and robustness in this direction in the context of smart sustainable cities. Indeed, smart sustainable urban planning is a new urban phenomenon that poses great challenges for traditional approaches to modeling and simulation. This is due to the fact that smart sustainable cities are shifting the focus from physical actions to data-centric actions, in addition to many urban functions becoming automated and thus data computation and intelligence blended with human actions. In fact, the materialization of smart sustainable cities is pushing for more sophisticated simulation models. This is due to several reasons, namely the big data provided from city functions offer “the prospect of a world in which the implications of how the city is functioning is continuously available and such immediacy is compressing time scales in such a way that longer term planning itself faces the prospect of becoming continuous as data is updated in real time”; and “the prospect of developing intelligence and planning functions at the same time as the very object that we are concerned with the city is changing its nature due to similar if not the same functions being used in its operation. This kind of space-time convergence in cities implies a level of complexity that only the new and powerful science of the kind that we will pioneer in *future ICT* can address." (Batty et al. 2012, p. 497)

One of the class of models under investigation is the cellular automata models of urban planning and agent-based models of spatial behavior in relation to transportation modeling. Batty et al. (2012) are working on using and extending the agent-based micro-simulation MATSim, which provides a basis for extensive model implementation that strongly links different weakly hitherto connected travel behavior, land use, mobility patterns, and social networks. They state that "other classes of more aggregate land use transportation models (such as the Simulacra suite of models)…will be extended and linked to more disaggregate physical models. These simulate aggregate dynamics of development and we envisage that models of this kind can be linked to models of the MATSim variety. This style of model will be used to demonstrate how new planning and decision support systems can be fashioned for planning the smart (sustainable) city." (Batty et al. 2012, p. 510)

In sum, one of the significant scientific challenges of smart sustainable cities is to provide portfolios of simulation that inform their future designs on the basis of predictive insights and forecasting capabilities. This involves building and aggregating several urban simulation models of different situations of urban life pertaining to the way existing urban systems can be integrated and different urban domains can be coordinated, as well as to how human mobility data can be linked to spatial organizations, transport systems and networks, travel and commuting behavior, socioeconomic network performance, environmental performance, and land use. This should be done in connection with the vision of sustainability as a holistic thinking approach. All in all, the idea of ICT becoming constitutive and integrative to improve sustainability performance (or make urban living more sustainable) is central to the quest for making smart sustainable cities function as a social organism (Batty et al. 2012; Correia and Wuenstel 2011) by design in terms of their physical, infrastructural, operational, and functional aspects.

6.12 Urban Design Perspectives in Light of Systems Thinking

One of the purposes of using systems thinking to foster a deeper understanding and create fertile insights in relation to smart sustainable cities is to make visible possible places for actions that can improve their contribution to the goals of sustainable development, as well as to provide a framework for designing the best vehicles for implementation. With that in regard, the use of ICT to develop new urban intelligence functions as new conceptions of the way smart sustainable cities function and make use of the complexity sciences in fashioning powerful new forms of optimization strategies and simulation models that generate urban structures and forms that improve sustainability (e.g., Batty et al. 2012; Bibri and Krogstie 2016, 2017b) should be supported by relevant urban design concepts, principles, and approaches to strengthen these structures and forms in terms of their practicality as to the contribution to sustainability. In short, it is important to effectively amalgamate urban design constructs and methods with advanced technologies and their novel applications based on big data analytics. Urban design concepts and principles have been adequately discussed in Chap. 2, and the focus in this subsection is on urban design perspectives in light of a systems thinking view.

6.12.1 Urban Design Problem and Process

In the domain of sustainable urban planning and development, design is interpreted in multiple ways, with different meaning within different areas, including landscape architecture, built environment, industry, and social innovation. Regardless, design is contextual and situated, serves various stakeholders, deals with discursive rather than objective criteria, and changes social reality purposefully. Design problem is about resolving the tension between what can be done and what is needed to be done given that most of urban problems, whether physical, environmental, economic, and social, are ill-structured or wicked problems (see Rittel and Webber 1973). That is, such problems do not yield one design solution because they mirror real-world situations where issues tend to be complex, conflicting, volatile, and intertwined. Hence, there is no perfect solution to design problems concerning urban sustainability, and each solution contains strengths and weaknesses. Indeed, design is a dynamic process used to create solutions through research, conceptualization, prototyping, validation, implementation, and improvement. The outcome is more often than not informed by perspectives drawn form systems thinking in terms of, for example, what design should stress as criteria in line with the vision of sustainability as a holistic thinking approach. The purpose of urban design is to enhance the sustainability performance of urban forms through their underlying typologies and design concepts and what these entail in terms of spaces, facilities, networks, processes, services, and so on, in addition to environmental and management systems (see Chap. 7 for further details). In this sense, design is conceived as an innovative problem solving activity, one in which solutions can be created in response to different physical, environmental, social, and economic problems, and to ultimately fulfill human needs. Different ways of urban design lead to different ways of using the built environment. This implies that design intentions have environmental, social, and economic implications.

6.12.2 Urban Design Perspectives

Sustainable urban planning and development involves a wide variety of design perspectives that are informed by systems thinking as a field of study. Designing man-made systems is based on the application of the knowledge acquired from the study of systems in the observable world (M'Pherson 1974), so is the approach to design. This includes in the domain of urban sustainability such perspectives as participatory design, multi-stakeholder design, biomimetic design, and multi-scalar design. These can be combined depending on several dimensions for consideration, as well as on the domain on focus, such as social innovation, landscape architecture, built environment, and industry.

Participatory design and multi-stakeholder design perspectives are the most commonly used in social innovation associated with sustainability. They tend to overlap in many aspects and are often combined because of the complexity of social problems being addressed as instances of wicked problems. Participatory design is described as a democratic, cooperative, interactive, and contextual design approach (e.g., Bibri 2015). Indeed, design for social innovation involves user participation and democratic involvement, as well as "Thinging" and "Infrastructuring", "agnostic public spaces", and prototyping (Björgvinsson et al. 2010; Hillgren et al. 2011; Mouffe 2000). Participatory design allows users to be actively involved as codesigners of solutions, such as products, services, and models; support socio-material working relations; establish long-term relationships and collaborations; and help evoke dilemmas. For example, with "infrastructuring" (Hillgren et al. 2011), urban design becomes an open-ended long term process where diverse stakeholders can innovate together because it creates platforms that make it easy to assemble heterogeneous teams—civic and public servants, designers, citizens, research institutions, and firms—to collaboratively codesign new solutions in response to a variety of social problems. This is of high relevance to smart sustainable cities in terms of social sustainability. In addition, social innovation represents democratizing innovation practice in line with the vision of participatory design in the sense of providing an open innovation milieu where new ideas emerge from bottom-up, long-term collaborations amongst multiple stakeholders (Björgvinsson et al. 2010). This entails, among others, involving different users and communities as experts in their domain in the design of sustainability solutions.

As a value-based vision of sustainability, Cradle-to-Cradle (C2C) design (McDonough and Braungart 2003) is a biomimetic approach and applicable to industry and architecture in the domain of sustainable urban planning and development. As to industry, C2C posits that products, processes, and systems are to be economically useful, socially beneficial, and environmentally intelligent. This vision can be realized by applying the 12 principles of green engineering (e.g., Abraham and Nguyen 2003). It builds on the idea of imitating nature as to material flow, energy use, recycling, and so forth. In relation to architecture, C2C design is seen as an ecologically intelligent approach that involves materials, buildings, and urban forms that are healthful and restorative. It helps to create buildings and community plans that generate a diverse range of environmental, social, and economic values.

Spatial multi-scalar approach is important in the planning of sustainable urban forms (Kärrholm 2011). It aims at maximizing the positive outcomes and minimizing the negative ones. It is of significance to consider different multi-scaling and scalar relations when implementing the principles of sustainable urban development, such as the typologies and design concepts of sustainable urban forms (see Chap. 2 for an overview). Addressing wicked urban problems at a certain scale may improve the situation at that scale, but can have adverse effects on a larger scale (see Chap. 5 for further discussion). In this case, it is necessary to look at the possible outcomes on different scales prior to design. In addition, flexible material design, coupled with largest number of territorial productions, affects the patterns and dynamics of the accessibility of public spaces (Kärrholm 2007). With regard to the materiality of territorially, territorial strategies should promote accessibility, sociability, safety, diversity, interconnectivity, and adaptability as methods to achieve sustainable cities (Kärrholm 2007).

6.13 Conclusions

Smart sustainable cities are one of the most complex systems and dynamically changing environments. Therefore, it is important to adopt advanced thinking approaches into explaining how they behave, evolve, and interact with the environment so as to create suitably sophisticated methods that can effectively direct their collective behavior and development in ways that enable them to maintain themselves at the required level of sustainability. Indeed, sustainability in its literal means an ability of a system that can be maintained or sustain itself indefinitely. This implies integrating natural systems with human systems in terms of patterns, behaviors, and relationships and celebrating continuity.

The principal aim of this chapter was to systematically explore the key underlying structures, behavioral patterns, conditions, relationships, and interactions pertaining to smart sustainable cities as complex systems, and to elucidate the related principles in terms of methods, mechanisms, and goals, based on systems thinking and complexity science as theoretic approaches. This chapter also discussed the potential of big data analytics and related urban intelligence functions and urban simulation models for, and the role of urban design in, catalyzing and advancing the strategic process of sustainable development by proposing innovative approaches and solutions for monitoring, managing, planning, and designing smart sustainable cities of the future. Thinking systematically has served to foster a deeper level of understanding of smart sustainable cities as complex systems by surfacing noteworthy internal, external, and reciprocal relationships as well as their implications for sustainability. This has enabled to make visible possible places for actions that can improve their contribution to the goals of sustainable development. These actions involve a set of advanced approaches and solutions necessary for enhancing their functioning and adaptation in ways that guide their development toward the desired state of sustainability. This can be accomplished by means of devising powerful urban intelligence functions and robust urban simulation models based on big data analytics for strategic decision-making in conjunction with adopting urban design for sustainability concepts, principles, and approaches. The latter are intended to strengthen the structures and forms that advance sustainability, as well as to operationalize and implement them as alternative or enhanced ones are to be generated by urban simulation models and optimization strategies enabled by urban intelligence functions as new conceptions of the way smart sustainable cities function and utilize complexity science. This pertains to novel and robust typologies of sustainable urban forms and their effective integration with new technologies and their big data applications (Bibri and Krogstie 2017b). Urban design for sustainability aims to develop and redevelop cities in ways that provide a healthy and livable environment with minimized demands on material and energy resources and minimized impacts on the environment. This goal can be further achieved by applying sophisticated methods based on big data analytics as an advanced form of ICT. To go about designing smart sustainable cities requires adopting and amalgamating a set of design perspectives informed by systems thinking, most notably participatory, multi-stakeholder, multi-scalar, and biomimetic approaches as the best vehicles for realizing holistic design ideas, whether created by humans or generated by computers. In all, both big data applications and urban design approaches are of crucial importance to tackling the complex challenges and intractable problems pertaining to sustainability and urbanization through effectively monitoring, understanding, analyzing, planning, and developing smart sustainable cities in ways that allow to strategically assess their contribution to the goals of sustainable development and to direct their collective behavior and the relationship they form with the environment in line with the vision of sustainability.

The urban sustainability problems are highly likely to yield as we reclaim our holistic thinking and apply it using advanced ICT that can enable us to see the systems of smart sustainable cities as the source of their own problems, and find the astuteness and wisdom as well as the technical brilliance and intelligence to restructure them and reshape their interaction in ways that allow them to achieve sustainability. Especially, most of such problems are intrinsically systems problems —undesirable patterns of behavior characteristic of the system structures and the reciprocal relationships resulting from profound interactions that produce them. Besides, sustainability has systemically proved powerful in terms of integrating natural systems with human systems to attain once inconceivable goals by urging the key societal actors to conduct their economic affairs in the best interest of the environment and the people as a whole. Sustainability goals are always presented in terms of the environment, the economy, and equity, and crucially, the well-being of these three areas must be interrelated rather than separate, an idea which rests on understanding the interdependence and equal importance of the natural environment, the economy, and society (Bibri 2015).

The importance for being aware of complexity science resides in that urban sustainability involves complex issues and scenarios related directly to the properties and behaviors of cities as a set of independent yet interconnected systems and domains. Smart sustainable cities have been described as complex systems par excellence, being dynamic, nonlinear, multidimensional, and constituent of subsystems connected and joined together by a web of relationships, among others. With a complexity science perspective, there is an appreciation of the relationships, interactions, or dependencies occurring within smart sustainable cities between their components. Considering the environmental and socioeconomic issues of sustainability and urbanization, there are a multitude of complex factors and links that contribute to urban problems. Therefore, city planning and development interventions and programs require an approach that can account for the complexity of such problems. Indeed, urban planners and ICT experts involved in mart sustainable cities can be more effective if they shun reducing problems to their smaller parts and alternatively attempt to understand the complex relationships that are occurring. If they embrace complex systems thinking, solutions can be designed and studied to address the complex challenges of sustainability and urbanization facing all classes of modern and future cities. As Dekker (2010, p. 148) puts it, "Complexity theory says that if we really want to understand failure in complex systems, we need to… explore how things are related to each other and how they are connected to, configured in, and constrained by larger systems of pressures, constraints, and expectations." Instead of responding to sustainability and urbanization issues with a reductionist approach, complexity science provides a perspective that acknowledges and embraces the challenge of complexity. Importantly, while complexity science is an emerging approach, practical applications of its approach do exist and have been used in several domains.

We argue that systems thinking and complexity science are integral to the understanding of smart sustainable cities, which is a moving target in that they are becoming more complex through the very technologies being used to understand them. Moreover, advanced ICT is founded on the application of complexity science to urban problems in terms of tracking the changing dynamics, disentangling the intractable problems, and tackling the challenges pertaining to urban systems which are in and of themselves becoming ever more complex. As high-performance computers have become an indispensable source of information, complex systems cannot be studied without the use of computers and hence big data analytics. This together with urban intelligence functions and urban simulation models constitute new conceptions of how smart sustainable cities can perform in terms of their operational functioning and planning with regard to steering their collective behavior in ways that continuously improve their contribution to the goals of sustainable development and to ultimately evolve into a sustainable state. It is hoped that the resource offered in this chapter contributes to the ongoing endeavors and programs concerning the design and development of smart sustainable cities of the future.

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Chapter 7
Sustainable Urban Forms: Time to Smarten up with Big Data Analytics and Context–Aware Computing for Sustainability

Abstract ICT is becoming increasingly spatially all pervasive, located anywhere and everywhere across urban environments, thereby providing the necessary basic infrastructure backbone for cities to realize their full potential in terms of sustainability through innovative solutions. As a consequence, data sensing and information processing are being fast embedded into the very fabric of contemporary cities while wireless networks are proliferating on a hard-to-imagine scale. This has been fueled by the new digital transition in ICT enabled by various forms of pervasive computing and driven predominantly by big data analytics and context-aware computing. This has in turn been justified by their underlying tremendous potential to enhance urban operations, functions, designs, services, strategies, and policies in line with the vision of sustainability. Further, while sustainable development has inspired a generation of scholars and practitioners in different disciplines into a quest for the immense opportunities created by the development of sustainable urban forms for human settlements, there are still significant challenges that need to be addressed and overcome. The issue of such forms has been problematic and difficult to deal with, particularly in relation to the improvement of their contribution to the goals of sustainable development. In addition, given that smart sustainable cities are a new techno-urban phenomenon, there is a need for analytical frameworks merging the physical and informational landscapes of such cities. This can play a role in spurring their development and deployment based on big data analytics and context-aware computing. The purpose of this chapter is twofold. First, this chapter intends to examine and substantiate the potential of big data analytics and context-aware computing to improve urban sustainability. This entails integrating the big data and context-aware applications of smart sustainable cities with the typologies and design concepts of sustainable urban forms to achieve multiple hitherto unrealized smart targets or in ways that intelligently improve the contribution of sustainable urban forms to the goals of sustainable development. In doing so, we offer a conceptual framework in the form of a matrix of smart sustainable urban form to help planners and scholars in understanding and analyzing how the contribution of such form to sustainability can be improved with the support of advanced forms of ICT. Second, this chapter

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explores the opportunity of merging the physical and informational landscapes of smart sustainable cities to achieve the goals of sustainable development. Accordingly, two analytical frameworks are proposed, in which the components of the physical landscape of sustainable urban forms and those of the informational landscape of smart sustainable cities are identified on the basis of a thematic analysis and then merged together to enable and support data-centric and context-aware applications across urban systems and domains in the context of sustainability. Specifically, the study identifies two most influential technologies and their applications pertaining to models of the smart sustainable city as well as three design concepts and four typologies related to models of sustainable urban form.

Keywords Smart sustainable cities · Sustainable urban forms · Big data analytics Context-aware computing · ICT · Urban sustainability · Data-centric and context-aware applications · Typologies and design concepts · Physical landscape Informational landscape · Urban systems and domains

7.1 Introduction

Smart sustainable cities as an emerging holistic urban development approach open new windows of opportunity and offer the types of insights which scholars, policymakers, and practitioners need in order to bring about sustainability transitions, as they constitute key sites of environmental, economic, and social innovation making significant contributions to urban transformation in the twenty-first century. The basic idea of smart sustainable cities revolves around leveraging the advance and prevalence of ICT in the transition toward the needed sustainable development in an increasingly urbanized world. Therefore, the development of smart sustainable cities is gaining increasing attention worldwide from research institutes, universities, governments, policymakers, and ICT companies as a promising response to the imminent challenges of sustainability and urbanization.

Scholars from different disciplines and practitioners from different professional fields have, over the past two decades or so, sought a variety of sustainable city models that can contribute to sustainability and its continuous improvement in response to the rising concerns about the environment and socioeconomic needs. Compact city, eco-city, and new urbanism (e.g., Jenks et al. 1996a, b; Neuman 2005; Register 2002; Joss 2010, 2011; Joss et al. 2013) are the most prevalent sustainable urban forms (e.g., Jabareen 2006; Rapoport and Verney 2011; Kärrholm 2011). They can be achieved through a combination of such typologies as density, compactness, diversity, and mixed land use, supported by sustainable transport, ecological design, and solar passive design as design concepts, as well as high standard environmental and urban management systems (e.g., Jabareen 2006). However, the underlying challenge continues to motivate and induce scholars and practitioners, as well as policymakers and decision-makers, to work collaboratively to put forward new approaches into redesigning and rearranging urban areas across many spatial scales to achieve the required level of sustainability, especially in relation to integrating its physical, environmental, economic, social, and cultural dimensions (Bibri and Krogstie 2017a, b). The ultimate goal revolves around producing more convincing and robust models of sustainable urban form, which has been one of the most significant intellectual challenges for more than two decades (see, e.g., Bibri and Krogstie 2017a; Jabareen 2006; Kärrholm 2011). Outlining a distinctive set of design concepts and typologies by which settlements can be classified in terms of their environmental burden as well as developing a sustainable urban form matrix as a tool for evaluating the sustainability of the existing models of sustainable urban form, Jabareen (2006, p. 48), concludes that "neither academics nor real-world cities have yet developed convincing models of sustainable urban form and have not yet gotten specific enough in terms of the components of such form." In recent years, it has become of high pertinence and critical importance, especially in an increasingly computerized and urbanized world, to augment sustainable urban forms with advanced ICT and its novel applications in a bid to advance the contribution of the underlying typologies and design concepts to the goals of sustainable development (Bibri and Krogstie 2017b). In light of the above, it has been difficult to translate sustainability into the built form of cities—without the use of advanced technologies (Bibri and Krogstie 2017b). In practice, many planning experts, landscape architects, and local city governments are grappling specifically with dimensions of such models by means of a range of urban planning and design approaches (Jabareen 2006; Kärrholm 2011). Indeed, whether in discourse, theory, or practice, the issue of sustainable urban form has been problematic and difficult to deal with, resulting in uncertain, weak, limited, divergent, non-conclusive, and contradictory results (Jabareen 2006; Kärrholm 2011; Neuman 2005), particularly when it comes to the actual effects of the claimed benefits of sustainability (Bibri and Krogstie 2017a, b).

In addition, the traditional sustainable urban planning approach alone is no longer of pertinence as to ensuring the effectiveness of the operation, management, assessment, administration, and design of urban systems with regard to addressing the challenge of sustainability or to continuously improving it due to the issues being engendered by the rapid urbanization. In relation to this, Neuman (2005) contends that conceiving cities in terms of forms remains inadequate to achieve the goals of sustainable development; or rather, accounting only for urban form strategies to make cities more sustainable is counterproductive. Instead, conceiving cities in terms of "processual outcomes of urbanization" holds great potential for attaining the goals of sustainable development, as this involves asking the right question of "whether the processes of building cities and the processes of living, consuming, and producing in cities are sustainable," which raises the level of, and may even change, the game (Neuman 2005). Townsend (2013) portrays urban growth and ICT development as a form of symbiosis. The process-driven perspective paves the way for a more dynamic conception of urban planning that reverses the focus on urban forms governed by static planning tools; this holds more promise in attaining the elusive goals of sustainable development (Neuman 2005). Existing sustainable urban forms as to the underlying typologies and design concepts tend to be static and fail to account for changes over time. A well-established fact is that cities evolve and the knowledge underlying their planning and design is perennially changing. In this regard, cities need to be scalable in their design and flexible and resilient in their functioning in response to population growth, environmental pressures, changes in socioeconomic needs (Bibri and Krogstie 2017a). Durack (2001) argues for open, indeterminate planning due to its advantages, namely tolerance and value of topographic, social, and economic discontinuities; citizen participation; and continuous adaptation, which is common to human settlements (Durack 2001). This can best be attainable through embedding ICT in planning processes for what it entails in terms of enabling and integrative tools.

Furthermore, in urban planning and policy making, "the concept of sustainable city has tended to focus mainly on infrastructures for urban metabolism-sewage, water, energy, and waste management within the city" (Höjer and Wangel 2015, p. 3), thereby falling short in considering smart solutions within various urban domains where such solutions can have a substantial contribution in the context of sustainability (Bibri and Krogstie 2017b). The concept of urban sustainability has long been promoted by systems scientists using the pragmatic framework for urban metabolism; smart urban metabolism as an ICT-enabled evolution of such framework is being implemented to overcome some of its limitations (Shahrokni et al. 2015). The purpose is to enhance and sustain the levels of sustainability of urban forms (Bibri and Krogstie 2017a). In all, there are several critical issues that remain unresolved, largely ignored, and underdeveloped for applied purposes with regard to the extent to which the challenge of urban sustainability can be addressed, despite the promotion of sustainable cities as a desirable goal within planning and policy contexts.

The main argument in the ongoing debate on sustainable urban forms is that urban systems are in themselves very complex in terms of their functioning, operation, management, and planning, so too are urban domains in terms of their coordination, integration, and coupling. Hence, it is timely and necessary to develop and employ more innovative solutions to deal with the challenges of sustainability and urbanization in the context of sustainable urban forms. This requires a blend of sciences for creating advanced and powerful engineering solutions, which ICT is extremely well placed to initiate for it is founded on the application of computer science, data science, systems thinking, and complexity science to urban systems and domains and related intractable problems (see, e.g., Batty et al. 2012; Bibri and Krogstie 2017a; Bettencourt 2014). One way forward to smarten up sustainable urban forms is to adopt the cutting-edge applications being offered by ICT of pervasive computing based on big data analytics and context-aware computing for sustainability (Bibri and Krogstie 2017b). The whole idea is that more innovative solutions are needed to overcome the kind of wicked problems associated with sustainable urban forms. In this regard, the main and relevant question is how such forms should be monitored, understood, analyzed, and planned to strategically advance their contribution to sustainability. In fact, with their domains becoming subtly interconnected and their processes highly dynamic, sustainable urban forms are relying more and more on sophisticated technologies, and in the near future, the core enabling technologies of ICT of computing will be the dominant mode of monitoring, understanding, analyzing, and planning sustainable cities (Bibri and Krogstie 2017b). In addition, cities are increasingly seen as adaptive and data-centric systems characterized by dynamic changes, complex interactions, and multidimensional effects. This is in contrast to what was the case for almost 50 years ago, when cities were still very much seen as unchanging structures and closed systems.

The role of ICT solutions in improving different aspects of sustainability is abundantly clear in light of the ongoing and future endeavors of both smart cities and sustainable cities (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017b, c, 2018; Bettencourt 2014; Kramers et al. 2014; Marsal-Llacuna et al. 2015; Shahrokni et al. 2015; Solanas et al. 2014). All in all, it has become theoretically and practically of high pertinence and importance to augment the design concepts and typologies of sustainable urban forms with smart applications for the purpose of increasing their contribution to the goals of sustainable development contribution under what is labeled "smart sustainable cities of the future." This is of high relevance to consider in an increasingly computerized and urbanized world. These insights are meant to stimulate research opportunities for rethinking the theoretical foundations of sustainable urban forms to enhance the existing practices given the relevant potential of emerging and future ICT. To note, though, it is well-substantiated by many urban scholars and practitioners that the adoption of design concepts and typologies of sustainable urban forms is necessary to achieve sustainability (e.g., Bibri and Krogstie 2017a, b; Hofstad 2012; Jabareen 2006; Joss 2011; Kärrholm 2011; Dumreicher et al. 2000; Leccese and McCormick 2000; Rapoport and Verney 2011; Williams et al. 2000)—in addition to employing smart technologies to enhance and integrate urban systems and to coordinate and couple urban domains to advance sustainability. The role of ICT (especially big data analytics and context-aware computing) as an enabling and constitutive technology lies in the substantial contribution it can make as to not only enhancing the operational functioning of sustainable urban forms, but also monitoring, understanding, analyzing, and planning such forms to strategically improve and sustain their contribution to sustainability. One of the key scientific challenges pertaining to smart sustainable cities is to relate the typologies and design concepts of sustainable urban forms to their operational functioning and planning through control, automation, management, and optimization (Bibri and Krogstie 2017b).

There exist several studies on the topic of big data analytics and context-aware computing technologies and their uses in the domain of urban management and planning, but they pertain in large part to the efficiency of solutions in the context of smart cities (e.g., Batty et al. 2012; Batty 2013a, b; Bibri and Krogstie 2017a; Kamberov 2015; Khan et al. 2015, 2013, 2014; Kitchin 2014; Solanas et al. 2014; Townsend 2013). Conversely, only a few studies have recently started to focus on the uses of such technologies in relation to sustainability in the context of sustainable urban forms and smart sustainable cities (e.g., Al Nuaimi et al. 2015; Bettencourt 2014; Bibri and Krogstie 2017a, b, c; Marsal-Llacuna et al. 2015). However, while a large part of research work on smart cities is currently focusing on a wide variety of technological propositions about what makes cities smart in terms of sustainability, this relationship is too often, if not always, addressed separately from the rather established strategies through which sustainable cities can be achieved, namely density, diversity, compactness, mixed land use, sustainable transport, ecological design, and passive solar design (Bibri and Krogstie 2017a, b). Furthermore, given that smart sustainable cities are a new techno-urban phenomenon, there is a need for analytical frameworks merging the physical and informational landscapes of such cities to advance their contribution to the goals of sustainable development (Bibri and Krogstie 2017a). This can play a pivotal role in laying the foundation for their development and deployment based on the amalgamation of big data analytics and context-aware computing as advanced technologies and their novel applications. Besides, research remains generally scant on the development of conceptual and analytical frameworks for smart sustainable cities based on big data analytics and context-aware computing.

As it is an urban world where the informational and physical landscapes are increasingly being merged, sustainable urban forms need to embrace and leverage what ICT of pervasive computing has to offer as innovative solutions so as to advance their contribution to sustainability. The need for ICT of computing to be embedded in such forms is underpinned by the recognition that urban sustainability applications are deemed of high relevance and salience to the contemporary research agenda of urban computing and ICT. To unlock and exploit the underlying potential and exploit such agenda, the field of sustainable urban development is required to extend its boundaries and broaden its horizons beyond the ambit of the built form of cities to include emerging and future technological innovation opportunities.

The aim of this chapter is twofold. First, this chapter intends to examine and substantiate the potential of big data analytics and context-aware computing to improve urban sustainability. This entails integrating the big data and context-aware applications of emerging smart sustainable cities with the typologies and design concepts of sustainable urban forms to achieve multiple hitherto unrealized smart sustainable targets, or in ways that intelligently improve the contribution of sustainable urban forms to the goals of sustainable development. In doing so, we offer a conceptual framework in the form of a matrix of smart sustainable urban form to help planners and scholars in understanding and analyzing how the contribution of such form to sustainability can be improved with the support of advanced forms of ICT. Second, this chapter explores the opportunity of merging the physical and informational landscapes of smart sustainable cities to achieve the goals of sustainable development. Accordingly, two analytical frameworks are proposed, in which the components of the physical landscape of sustainable urban forms and those of the informational landscape of smart sustainable cities are identified on the basis of a thematic analysis and then merged together to enable and support data-centric and context-aware applications across urban systems and domains in the context of sustainability. Specifically, the study identifies two most influential technologies and their novel applications pertaining to models of the smart sustainable city as well as three design concepts and four typologies related to models of sustainable urban form. The proposed analytical frameworks are intended for use by urban scholars, researchers, and planners as well as ICT companies interested in acquiring a better understanding of how big data analytics and context-aware computing could advance the sustainability of smart sustainable cities to the goals of sustainable development. The main motivation for this paper is to put forward novel solutions and useful suggestions for effectively translating sustainability into the various forms of smart sustainable cities of the future.

The remainder of this chapter is structured as follows. Section 7.2 outlines the thematic analysis approach and justifies its relevance to the study. Section 7.3 presents the outcome of the thematic analysis: the operational aspects (design concepts and typologies) of models of sustainable urban form and the operational facets (technologies and applications) of models of the smart sustainable city. In addition, it provides a short account of the applicability of context-aware computing and big data analytics to urban sustainability, i.e., the kinds of intelligence functionalities these two advanced technologies could provide to improve the contribution of smart sustainable cities to the goals of sustainable development. In Sect. 7.4, we describe and discuss the integration of the technologies and applications of models of the smart sustainable city with the typologies and design concepts of models of sustainable urban form to advance urban sustainability. We, moreover, offer a conceptual framework in the form of a matrix for illustrating this integration. Section 7.5 introduces, describes, and illustrates the two proposed analytical frameworks for merging the physical and informational landscapes of smart sustainable cities. Section 7.6 explains and discusses context awareness for physical service environments within smart sustainable cities. In Sect. 7.7, we provide a detailed description of the main components of the underlying physical and informational landscapes. Section 7.8 elucidates and reflects on implementation issues related to the proposed analytical frameworks based on big data and context-aware technologies and applications. Finally, we provide our conclusions together with some final thoughts in Sect. 7.9.

7.2 Research Approach: Thematic Analysis

It is assumed that in existing models of sustainable urban form and recent models of the smart sustainable city, there are concepts and technologies that repeat themselves and compose distinct models of such form and city, respectively, (Bibri and Krogstie 2017b). Therefore, this chapter uses a qualitative approach to identify the design concepts and typologies of sustainable urban forms as well as the technologies and applications of smart sustainable cities, and, eventually, to identify the urban concepts and technological constructs behind them. The purpose is to highlight how big data and context-aware applications can conceptually be merged with urban design and land use components to advance sustainability in the context of smart sustainable cities. In relation to the thematic analysis, the aim of qualitative studies is to describe and explain a pattern of relationships, a process that entails a set of conceptual categories (Mishler 1990) pertaining in this context to urban design and planning and urban computing and ICT.

Following a set of qualitative "tactics" suggested by Miles and Huberman (1994) that can assist in generating meanings from diverse material, a thematic analysis has been designed and employed with two purposes in mind: (1) to identify the design concepts and typologies of sustainable urban forms, and (2) to identify the technologies and applications of smart sustainable cities. Subsequently, it intends to conceptualize the theoretical base behind these urban and technological components. As an inductive analytic approach, thematic analysis can be used to address the different types of questions posed by researchers to produce complex conceptual cross-examinations of the underlying meaning in qualitative data. This can be done through discovering or finding patterns, relationships, themes, and concepts in large qualitative data entailing interdisciplinary or multidisciplinary literature. Thereby, thematic analysis is an appropriate approach when analyzing a large body of documents—in the form of, for example, conceptual frameworks, critical reviews, descriptive accounts, analytical accounts, and empirical research. It can be applied to produce theory-driven analyses and other analytical accounts.

The main steps of this chapter's thematic analysis approach are as follows:

1. Review of urban planning and design, urban computing and ICT, and urban sustainability and sustainable urban development, and other relevant multidisciplinary and interdisciplinary literature. This is to deconstruct related text associated with models of sustainable urban form and those of smart sustainable city (see Bibri and Krogstie (2017b) for an overview). The outcomes of this process are various design concepts, typologies, applications, and themes that are related to these two classes of models in relevance to their contribution to the goals of sustainable development.
2. Pattern recognition entails the ability to discover meaningful patterns and relationships in seemingly random information, and the purpose is to note key patterns and relationships as well as concepts within the result of the first step, and then to look for similarities within the sample and code the results by concepts (i.e., typologies, design concepts, big data applications, context-aware applications).
3. Conceptualization is about finding theoretical relationships among the identified urban and technological concepts associated with sustainability and thus generating theory-driven analytical framework.

7.3 Thematic Analysis Results

The thematic analysis has identified four typologies and three design concepts along with significant themes related to different dimensions of sustainability in the context of sustainable urban forms (see Bibri and Krogstie (2017b) for a detailed overview). It has moreover identified two technologies and their applications. These are similarly associated with themes pertaining to different aspects of sustainability in the context of smart sustainable cities (see Bibri and Krogstie (2017b) for a detailed overview).

7.3.1 Typologies and Design Concepts of Models of Sustainable Urban Form and Related Themes

Existing models of sustainable urban forms are designed primarily to lessen energy consumption, reduce GHG emissions, and lower pollution and waste levels, while improving human life quality. To achieve sustainable urban forms requires such typologies as compactness, density, diversity, and mixed land use, and such design concepts as sustainable transport, ecological design, and passive solar design, supported by high standards of environmental and urban management systems (Dumreicher et al. 2000; Jabareen 2006; Williams et al. 2000). Jabareen (2006) classifies sustainable urban forms into four models entailing overlaps among them in their concepts, ideas, and visions: (1) compact city, (2) eco-city, (3) neo-traditional development or new urbanism, (4) and urban containment. This taxonomy has been revisited by Bibri and Krogstie (2017b) from a technological perspective, i.e., ICT of the new wave of computing and its novel applications pertaining to big data analytics and context-aware computing. The focus in their work is on the first three urban forms in terms of integrating the underlying typologies and design concepts with such applications. The rationale behind their focus is that in the literature, the compact city is conceptually ranked as the most sustainable, followed by the eco-city, and then the new urbanism. Compact city emphasizes density, compactness, and mixed land use; eco-city focuses on ecological and cultural diversity, passive solar design, renewable resources, urban greening, environmental management, and environmentally sound policies; and new urbanism emphasizes sustainable transportation, mixed land use, diversity, compactness, and greening (Jabareen 2006). In the context of this chapter, the typologies and design concepts of sustainable urban forms are associated with the very bottom of the proposed analytical framework in the sense that urban systems and domains are to function and be managed together with these typologies and design concepts in the context of smart sustainable cities of the future. The effects of models of sustainable urban form and big data applications are compatible with the goals of sustainable development, and involve transport provision, travel behavior, mobility, accessibility, energy efficiency, pollution reduction, economic viability, life quality, and social equity (Bibri and Krogstie 2017b).

7.3.1.1 Compactness

The notion of compactness of the built environment or urban space is a widely acceptable strategy for achieving more sustainable urban forms. It signifies that future urban development should be driven by contiguity and connectivity in the sense of taking place adjacent to existing urban structures (Jabareen 2006; Wheeler 2002). It also refers to the containment of further sprawl when the concept is applied to existing rather than new urban fabric (Hagan 2000). As major themes evident in current debates on compactness as a strategy for achieving desirable urban forms, the positive effects of sustainability include the following (Bibri and Krogstie 2017b):

- Promoting the quality of life in terms of social interaction and accessibility to facilities and services
- Providing building densities for energy conservation
- Minimizing the number and length of trips by modes of transport (involving energy, materials, water, products, and people) detrimental to the environment in terms of CO_2 emissions
- Protecting rural land.

7.3.1.2 Density

As a critical typology of sustainable urban forms, density denotes the ratio of dwelling units or buildings and their inhabitants to land area (e.g. Bibri and Krogstie 2017b). As major themes evident in current debates on density as a strategy for achieving desirable urban forms, the claimed sustainability benefits involve the following (Bibri and Krogstie 2017b):

- Saving energy by slashing its consumption
- Achieving urban efficiency
- Minimizing automobile travel needs and thus emissions
- Providing accessibly with facilities and services.

7.3.1.3 Mixed Land Use

Widely recognized among scholars and planners for its important role in achieving sustainable urban form, mixed land use (heterogeneous zoning) signifies the diversity and proximity of land uses in terms of functioning, such as institutional, infrastructural, cultural, residential, commercial, and industrial (Bibri and Krogstie 2017b). As major themes evident in current debates on mixed land use as a strategy for achieving desirable urban forms, the positive effects of sustainability include the following (Bibri and Krogstie 2017b):

- Enhancing accessibility to services and facilities
- Reducing automobile use for various purposes
- Decreasing the travel distances between activities
- Encouraging cycling or walking
- Improving security in public spaces for disadvantaged groups
- Reducing air pollution and traffic congestion
- Stimulating the interaction of residents by increasing pedestrian traffic
- Decreasing vehicle trip generation rates and traveled time.

7.3.1.4 Diversity

Diversity is widely adopted by several planning approaches, such as new urbanism, sustainable urbanism, and smart growth. Overlapping with mixed land uses in urban planning, diversity entails, in addition to a mixture and multiplicity of land uses, building densities, a variety of housing types, housing for all income groups through inclusionary zoning, job-housing balances, household sizes and structures, cultural diversity, and age groups (e.g. Jabareen 2006; Wheeler 2002), thereby epitomizing the sociocultural context of the urban form (Bibri and Krogstie 2017b). As major themes evident in current debates on diversity as a strategy for achieving desirable urban forms, the corollaries of sustainability include the following (Bibri and Krogstie 2017b):

- Reducing traffic congestion and air pollution
- Encouraging walking and cycling
- Enhancing the quality of life in terms of social interaction.

7.3.1.5 Sustainable Transport

It has been argued that transport is the major issue for environmental debates relating to urban form (Jenks et al. 1996a, b). Sustainable transportation is described by Jordan and Horan (1997, p. 72) as "transportation services that reflect the full social and environmental costs of their provision; that respect carrying capacity; and that balance the needs for mobility and safety with the needs for access, environmental quality, and neighborhood livability." Among the major themes evident in current debates on sustainable transportation as a strategy for achieving sustainable urban forms, include the following (Bibri and Krogstie 2017b):

- Operating transport at maximum efficiency
- Providing favorable conditions for energy-efficient forms of transport
- Reducing the need for mobility
- Providing equitable access to services and facilities
- Limiting CO_2 emissions and waste
- Promoting renewable energy sources

- Decreasing travel needs and costs
- Minimizing land use
- Achieving a healthy and desirable quality of life
- Supporting a vibrant economy
- Conserving energy in several ways.

7.3.1.6 Greening-Ecological Design

Green urbanism or infrastructure is an important design concept in sustainable urban planning. Green space has the ability to contribute positively to sustainability agenda (Swanwick et al. 2003). There are key themes evident in current debates on greening urban spaces as a strategy for achieving desirable urban forms, which pertain to sustainability benefits and encompass the following (Bibri and Krogstie 2017b):

- Making urban places attractive and pleasant as well as more sustainable
- Bringing nature into the life of citizens through diverse open landscapes
- Moderating urban climate extremes
- Preserving and enhancing the ecological diversity of the environment of urban places
- Maintaining biodiversity through the conservation and enhancement of the range of urban habitats
- Improving the urban image and the quality of life
- Enhancing health benefits
- Ameliorating the physical urban environment by reducing pollution
- Increasing economic attractiveness in urban areas.

7.3.1.7 Passive Solar Design

The passive solar design is one of the key design concepts and principles for achieving a sustainable urban form. It entails reducing the demand for energy and the sustainable use of passive energy through particular design measures (Jabareen 2006). Among the major themes evident in current debates on passive solar design as a strategy for achieving sustainable urban forms, include the following (Jabareen 2006):

- Influencing airflow, view of sun and sky, and exposed surface area
- Influencing warming and cooling processes and pollution dispersal
- Influencing building heat gains and losses
- Influencing absorption, heat storage, and emissivity
- Influencing evaporative cooling processes on building surfaces and/or in open spaces
- Reducing and rerouting traffic to reduce air and noise pollution and heat discharge.

7.3.1.8 High Standards of Environmental and Urban Management

To achieve sustainable urban forms requires, in addition to the above typologies and design concepts, a range of management and development approaches, including the following:

- Environmental management systems
- Evaluation methods and practices
- Implementation strategies
- Simulation and operational models
- Environmental, social, institutional, and land-use policy instruments
- Tools and platforms for providing public services, social services, and cultural facilities
- Mechanisms for adherence to established regulatory frameworks
- Methods for practice improvements and policy recommendations.

7.3.2 Big Data Analytics and Context-Aware Computing Technologies and Their Applications

7.3.2.1 Key Big Data and Context-Aware Applications for Urban Sustainability

The prospect of developing and implementing smart sustainable cities based on big data analytics and context-aware computing as a set of technologies and applications is becoming increasingly a reality. This new techno-urban phenomenon is opening entirely new windows of opportunity for smart cities to explicitly incorporate sustainability and for sustainable cities to smarten up their contribution to sustainability. Smart sustainable cities as a techno-urban innovation represent transformative processes that have been fueled by the increasing infiltration of information intelligence into urban systems in terms of operations, functions, services, designs, practices, and policies. This information intelligence enabled and driven by big data analytics and context-aware computing could be leveraged in the advancement of urban sustainability by enhancing and integrating urban systems as well as by facilitating coordination and collaboration among diverse urban domains.

Accordingly, the two identified classes of applications of ICT of the new wave of computing pertain to big data analytics and context-aware computing in the context of smart sustainable cities. In other words, data-centric and context-aware applications constitute key components of the informational landscape of various models of the smart sustainable city (see Bibri and Krogstie (2017b) for a detailed account of these models). As noted by Bibri and Krogstie (2016b), their effects reinforce one another as to their efforts for bringing about sustainable transformation by employing advanced solutions for urban sustainability. The basic idea is that the opportunities for the deployment of the advanced solutions being offered by ICT of the new wave of computing are tremendous in the context of urban sustainability. Indeed, the applications associated with big data analytics and context-aware computing are compatible with the goals of sustainable development. They include, but are not limited to, the following:

- Data-centric and context-aware transport and mobility (e.g. Batty et al. 2012; Bibri and Krogstie 2016b; Dlodlo et al. 2012; Ghose et al. 2012; ISTAG 2003, 2008; Lee et al. 2008; Ren et al. 2012; Riva et al. 2008; Shang et al. 2014; Vongsingthong and Smanchat 2014)
- Data-centric and context-aware traffic lights and signals (e.g., Al Nuaimi et al. 2015; ISTAG 2003; Kumar and Prakash 2014)
- Data-centric and context-aware energy systems (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Ersue et al. 2014; ISTAG 2003; Parello et al. 2014)
- Data-centric and context-aware grid (e.g., Al Nuaimi et al. 2015; Ersue et al. 2014; ISTAG 2008; Mohamed and Al-Jaroodi 2014; Parello et al. 2014; Yin et al. 2013)
- Data-centric and context-aware environment (e.g., ISTAG 2003; Li et al. 2011; Zheng et al. 2013)
- Data-centric and context-aware buildings (e.g., Bibri and Krogstie 2016a, b; ISTAG 2008)
- Data-centric and context-aware public safety and civil security (ISTAG 2003; Shepard 2011)
- Data-centric and context-aware planning and design (e.g., Batty et al. 2012; Bibri and Krogstie 2017b; Nielsen 2011; Shahrokni et al. 2015)
- Data-centric and context-aware health care (Bibri 2015b; Solanas et al. 2014; Vongsingthong and Smanchat 2014; Zheng et al. 2014, 2013)
- Data-centric and context-aware education and learning (e.g., Al Nuaimi et al. 2015; Bibri and Krogstie 2016a; ISTAG 2003; Lee et al. 2008)
- Data-centric and context-aware citizen services (the quality of life) (e.g., Al Nuaimi et al. 2015; Kamberov 2015; Khan et al. 2015; 2014; Solanas et al. 2014)
- Data-centric and context-aware urban infrastructures and facilities monitoring and management (e.g., Chui et al. 2014; Ersue et al. 2014; Gubbi et al. 2013).

In all, the application of big data analytics and context-aware computing in smart sustainable cities offers the prospect of significantly improving different aspects of sustainability. One of the core ideas underlying the use of these advanced technologies is to integrate and harness solutions and approaches through coordinating, coupling, and integrating urban domains. Hence, exposing big data and context information via a sustainable, socially synergistic, evolvable, dynamic, extensible, scalable, and reliable ecosystem offers a wide range of benefits and opportunities with respect to urban sustainability. As noted by Bibri and Krogstie (2017a) with reference to sustainable urban forms, ICT of the new wave of computing as a set of enabling and constitutive technologies can make substantial contributions—not only in terms of catalyzing and boosting the development processes of sustainable urban forms, but also in terms of monitoring, understanding, analyzing, and planning such forms in ways that strategically evaluate, improve, and sustain their contribution to sustainability.

7.3.2.2 Big Data and Context Information Applicability to Urban Sustainability

Big data analytics and context-aware computing are associated, yet at both varying and overlapping degrees, with intelligent decision support and optimization strategies. These pertain to a wide variety of applications intended for controlling, automating, managing, planning, and enhancing urban systems, processes, and services in relation to diverse urban domains (transport, mobility, traffic, communication, energy, environment, healthcare, education, water, waste, land use, public safety, etc.). With its underlying big data analytics and context-aware computing as a set of advanced applications, ICT of pervasive computing is aimed at optimizing the energy efficiency of systems across urban domains, enhancing the operation of urban infrastructures and facilities, managing natural resources, reducing traffic congestion, lowering pollution and waste levels, improving the quality of life and well-being, and assessing and improving urban strategies and policies. This can be achieved by using both big data and context information as part of the analytical and computational processing pertaining to the functioning and operation of smart sustainable cities as complex and dynamic systems, depending on the application domain.

One of the most significant challenges pertaining to smart sustainable cities is to develop powerful intelligence functions as advanced forms of decision support based on big data analytics, which enable urban monitoring, management, and planning in the context of sustainability (Bibri and Krogstie 2017b). Developed through advanced ICT, such functions are associated with the process of fashioning new forms of simulation models by exploring many different kinds of modeling approaches as well as advanced optimization strategies—based on computer science, data science, and complexity sciences—that generate urban forms and structures that enhance different aspects of sustainability (Batty et al. 2012; Bibri and Krogstie 2017a, b). Developing intelligence functions allows additionally to explore the idea of smart sustainable cities as techno-urban innovation labs (see Bibri and Krogstie 2017a). Such functions can take the form of centers for scientific research and innovation with the primary purpose of continuously improving the contribution of smart sustainable cities to sustainability thanks to the prospect of building models of real-time cities in terms of their functioning on the basis of sensor-based/machine-generated data becoming clear and achievable.

Context-aware computing is at the core of urban intelligence due to its ability to equip smart applications and systems across various urban domains with the functionality of controlling, optimizing, and managing different aspects of the operational functioning of smart sustainable cities in relation to the goals of sustainable development. This occurs through reasoning on relevant context information using advanced dynamic models together with sensor readings to generate inferences, which can be used to guide decisions and knowledgeable actions in this regard. The reasoner takes as inputs sensor observations in conjunction with models of the very systems that the context data pertain to, and performs reasoning to provide incremental progressive context recognition concerning urban systems and citizens, depending on the type and scale of context-aware application. To support fine-grained urban context recognition, concrete sensor observations are bound with urban context models to create various context descriptions. By reasoning the descriptions against relevant urban profiles, specific urban contexts can be recognized. The resulting models enhance the capabilities of automated processing and the level of automation by allowing systems/agents to interpret context data/information and reason against context models, thereby enabling knowledge-based intelligent decision support pertaining to the improvement of different aspects of sustainability in connection with urban systems performance and service delivery.

Similarly, the common types of big data analytics include predictive, diagnostic, descriptive, and prescriptive analytics. These are applied to extract different types of knowledge or insights from large datasets, which can be used for different purposes depending on the application domain. The resulting knowledge can be used for supporting or automating decisions as well as for enhancing existing practices, strategies, and policies. As the most applied big data analytics technologies d in the urban domain, data mining as the automated extraction of useful knowledge from large datasets is associated with advancing the contribution of smart sustainable cities to the goals of sustainable development through knowledge-driven or well-informed decision-making processes pertaining to diverse urban systems and domains. In more detail, the process of data mining targets optimization and intelligent decision support related to the control, optimization, management, and planning of urban systems as operating and organizing processes of urban life, as well as to the enhancement of the associated ecosystem and human services pertaining to utility, healthcare, education, safety, and so on. This occurs through the implementation of simulation models, optimization strategies, and decision-making processes. Additionally, the process targets the improvement of practices, strategies, and policies by changing them based on new trends and emerging shifts. In all, the related analytical outcomes serve to improve urban operational functioning, optimize resources utilization, reduce environmental risks, and enhance the quality of life and well-being of citizens.

7.4 Merging Big Data and Context-Aware Applications with Typologies and Design Concepts

The shaping role and influence of ICT of the new wave of computing—considering its constitutive nature and transformational impact—will grow even more in contemporary and future cities, as the underlying technologies, infrastructures, and applications become more technically mature, financially affordable, and widely deployed in response to the increasing demand for urban sustainability solutions. Related innovative opportunities cannot be foreseen until UbiComp, AmI, the IoT, and SenComp technologies reach and permeate many spatial scales of sustainable urban forms. Here, the focus is on the sustainable ways in which all the systems and domains of such forms intricately interrelate, coordinate, and evolve. Indeed, such technologies usher in automation and intelligence in nearly all the systems and domains of smart sustainable cities, thereby finding applications in virtually all spheres of urban sustainability. That is to say, the range of urban sustainability applications that can utilize such technologies is potentially vast. Therefore, there are significant opportunities for UbiComp, AmI, the IoT, and SenComp in relation to improving sustainable urban forms in terms of their contribution to the goals of sustainable development.

It is worth noting that the aforementioned big data and context-aware applications enabled by ICT of the new wave of computing are associated with much of what the typologies and design concepts of sustainable urban forms are intended to achieve in terms of sustainability effects and benefits. In other words, the impact of big data and context-aware applications involves most of the major themes in debates on compactness, density, mixed land use, diversity, sustainable transportation, passive solar design, and greening as important strategies through which sustainable urban forms can be achieved, in addition to urban management approaches. Of importance to underscore is that these themes are distilled based on several studies carried out over the past 25 years within the area of sustainable urban planning.

By linking these themes to the sustainability benefits of big data and context-aware applications, it becomes evident that there is tremendous potential to advance the contribution of sustainable urban forms to the goals of sustainable development—with the support of ICT of the new wave of computing. Indeed, the opportunities for the development of smart sustainable urban forms will be enormous: not only in terms of catalyzing and boosting the processes of sustainable urban forms for achieving the required level of sustainability—but also in terms of monitoring, understanding, probing, and planning such forms in ways that strategically evaluate and optimize their contribution to sustainability (Bibri and Krogstie 2017b). The latter involves combining the complexity and data sciences upon which the application of ICT of the new wave of computing is founded to analyze and interpret the potentially emergent factors that might affect (hinder) the advancement of this contribution, and then relevant solutions can be devised and applied to overcome potential bottlenecks and face unpredictable changes.

The proposed matrix (see Table 7.1) illustrates the relationship between the major themes pertaining to the typologies and design concepts of sustainable urban forms and the big data and context-aware applications enabled by UbiComp, AmI, the IoT, and SenComp (Bibri and Krogstie 2017b). The themes are the criteria of the proposed matrix. An option of big data application (BDA) or context-aware application (CAA) is assigned to each cell of the matrix to express the link between smart applications and each theme associated with typologies and design concepts in terms of the contribution to the same or slightly different aspect of sustainability. To note is that the same themes may figure in different typologies or design concepts, which indeed characterize existing sustainable urban forms that have overlaps among their visions, ideas, and concepts (e.g., Bibri and Krogstie 2017b; Jabareen 2006). Both themes and applications are the outcomes of a thematic analysis. As Table 7.1 shows, big data and context-aware applications tend to appear across different typologies and design concepts because both of such

Table 7.1 Smart sustainable urban form matrix: Improving the contribution of sustainable urban forms to sustainability

Typologies and design concepts (Themes)	Big data analytics	Context-aware computing
Density		
• Saving energy by slashing its consumption	BDA	CAA
• Achieving urban efficiency	BDA	CAA
• Minimizing automobile travel needs and thus emissions	BDA	CAA
• Providing accessiblity with facilities and services	BDA	CAA
Compactness		
• Promoting the quality of life in terms of social interaction and accessibility to facilities and services	BDA	CAA
• Providing building densities for energy conservation	BDA	CAA
• Minimizing the number and length of trips by modes of transport detrimental to the environment in terms of CO_2 emissions	BDA	CAA
• Protecting rural land	BDA	
Mixed land use		
• Enhancing accessibility to services and facilities	BDA	CAA
• Reducing automobile use for various purposes	BDA	CAA
• Decreasing the travel distances between activities	BDA	CAA
• Encouraging cycling or walking	BDA	CAA
• Improving security in public spaces for disadvantaged groups	BDA	CAA
• Reducing air pollution and traffic congestion	BDA	CAA
• Stimulating the interaction of residents by increasing pedestrian traffic	BDA	CAA
• Decreasing vehicle trip generation rates and traveled time	BDA	CAA

(continued)

Table 7.1 (continued)

Typologies and design concepts (Themes)	Big data analytics	Context-aware computing
Diversity		
• Reducing traffic congestion and air pollution	BDA	CAA
• Encouraging walking and cycling	BDA	CAA
• Enhancing quality of life in terms of social interaction	BDA	CAA
Sustainable transport		
• Operating transport at maximum efficiency	BDA	CAA
• Providing favorable conditions for energy-efficient forms of transport	BDA	CAA
• Reducing the need for mobility	BDA	CAA
• Providing equitable accessibility to services and facilities	BDA	CAA
• Limiting CO_2 emissions and waste	BDA	CAA
• Promoting renewable energy sources	BDA	CAA
• Decreasing travel needs and costs	BDA	CAA
• Minimizing land use	BDA	
• Achieving a healthy and desirable quality of life	BDA	CAA
• Supporting a vibrant economy	BDA	CAA
• Conserving energy in several ways	BDA	CAA
Greening		
• Making urban places attractive and pleasant as well as more sustainable	BDA	CAA
• Bringing nature into the life of citizens through diverse open landscapes	BDA	
• Moderating urban climate extremes	BDA	
• Preserving and enhancing the ecological diversity of the environment of urban places	BDA	
• Maintaining biodiversity through the conservation and enhancement of the range of urban habitats	BDA	
• Improving the urban image and the quality of life	BDA	CAA
• Enhancing health benefits	BDA	CAA
• Ameliorating the physical urban environment by reducing pollution	BDA	CAA
• Increasing economic attractiveness in urban areas	BDA	CAA
Passive solar design		
• Influencing airflow, view of sun and sky, and exposed surface area	BDA	
• Influencing warming and cooling processes and pollution dispersal		CAA
• Influencing building heat gains and losses		CAA
• Influencing absorption, heat storage, and emissivity		CAA
• Influencing evaporative cooling processes on building surfaces and/or in open spaces		CAA

(continued)

Table 7.1 (continued)

Typologies and design concepts (Themes)	Big data analytics	Context-aware computing
• Reducing and rerouting traffic to reduce air and noise pollution and heat discharge	BDA	CAA
High standards of environmental and urban management		
• Environmental management systems	BDA	
• Evaluation methods and practices	BDA	
• Implementation strategies	BDA	
• Environmental, social, institutional, and land-use policy instruments	BDA	
• Tools and platforms for providing public services, social services, and cultural facilities	BDA	CAA
• Mechanisms for adherence to established regulatory frameworks	BDA	CAA
• Methods for practice improvements and policy recommendations	BDA	

applications may relate to a given urban domain (or subdomain) that involve different typologies and/or design concepts, adding to the fact that each class of applications is associated with various urban domains. For example, for increasing urban sustainability by combining traditional and modern architecture, AmI-based networks and information processing platforms (using context-aware computing) control traffic, energy, environment, waste, and water (Böhlen and Frei 2009)—several sustainable cities (e.g., Masdar, Dongtan, and Hammarby Sjöstad) implementing new technologies in various domains are seen as idyllic “ecological solutions” (Rapoport and Vernay 2011).

The use of big data analytics and context-aware computing in conjunction with the typologies and design concepts of sustainable urban forms will play a significant role in increasing and maintaining the contribution of sustainable urban forms to sustainability. This is at the core of diverse areas of urban planning, including environmental planning, transportation planning, land-use planning, landscape architecture, policy recommendations, administration, and urban design, in addition to various aspects of urban operational functioning, such as natural resources management, infrastructures and facilities management, and public and social services provisioning. As to strategic thinking and research and analysis as additional areas of urban planning, they are more linked to big data analytics.

The smart sustainable urban form matrix in Table 7.1 provides insights into how sustainable urban forms can improve their contribution to sustainability with the support of ICT of the new wave of computing. Significantly, this is a tentative merger of the informational landscape of smart sustainable cities and the physical landscape of sustainable urban forms based on the literature review and not on empirical findings. Important to note is that the field of smart sustainable urban forms is still in its very early stages, and thus the research is in its infancy (Bibri and Krogstie 2017b). This implies that there are no concrete case studies to investigate or explore, nor is there a fair amount of scholarly inquiry done with respect to smart sustainable urban forms. In particular, no study has been conducted on the topic of smartening up sustainable urban forms—as reported by Bibri and Krogstie (2017a, b). Evidently, however, the matrix can be refined or enhanced as more evidence (e.g., empirical findings) comes to light with regard to how the existing themes and new (classes of) applications may support or complete each other to demonstrate the improvement of urban sustainability through smart solutions. This is anchored in the underlying assumption that many new technological solutions for urban sustainability will materialize in the future as a result of the global call for linking ICT development and innovation with the agenda of sustainable development, thereby justifying ICT investments by environmental concerns and socio-economic needs.

Although this chapter does not offer hard data to illustrate the integration of the typologies and design concepts of sustainable urban forms with the big data and context-aware applications pertaining to smart sustainable cities, it proposes a smart sustainable urban form matrix that aims to aid researchers, scholars, practitioners, and other groups involved in the field of sustainable urban planning in understanding and analyzing how the contribution of sustainable urban forms to sustainability can be improved based on advanced technologies in an increasingly computerized and urbanized world, as such technologies evolve over time and become widely deployed across urban environments.

7.5 Two Analytical Frameworks for Merging Physical and Informational Landscapes

7.5.1 On the Analytical Frameworks

The frameworks are derived based on the findings drawn from the thematic analysis as well as the technical literature review (see Chap. 3) in terms of sensor technologies, data processing platforms, and computing models. The outcome provides a mapping or traceability from those findings as well as justifies the link to the different layers/components of the frameworks. The thematic analysis provides a rationale for the different component/layers of the framework. It is worth noting that the layered approach to the proposed framework is based on the scientific literature in terms of the overall framework being used commonly in system architectures and infrastructures in the context of smart cities when it comes to big data solutions (see Bibri (2017) for a relevant survey). However, a layered approach is only one among other approaches to consider in this regard, and thus a hybrid, horizontal, or dynamic approach can also be explored, e.g., combining cloud and fog computing with various approaches into collecting and capturing urban big data from new varieties of digital access, including satellite-enabled GPS in vehicles and on citizens, satellite remote-sensing data, traces left from online transactions processing and related demand–supply situations, and scanning technologies.

It is important to elucidate how big data analytics and context-aware computing technologies can be applied to deploy the key intelligent applications in order to enhance the performance of the urban systems and domains that operate within sustainable urban forms as to the underlying operations, functions, services, designs, strategies, and policies in line with the goals of sustainable development under what is labeled “smart sustainable cities of the future.” The frameworks presented here are intended to provide more comprehensive solutions in terms of integrating the physical and informational landscapes of such cities. The proposed frameworks include urban systems and domains, from which big data and context information flow for storage and processing based on a cloud computing solution. The analytical and computational understanding outcomes resulting from knowledge discovery/data mining processes and reasoning and inference mechanisms, respectively, are intended to make, support, or automate decisions at varying degrees, depending on the application domain. The big data analytics and context information processing as a set of computational processes targeting optimization and intelligent decision support are associated with controlling, managing, and enhancing urban processes and operations, as well as with improving ecosystem and human services. These pertain to the city operational functioning and management with regard to infrastructures, facilities, and resources, and to the city services directed for providing a better quality of life and well-being to citizens—in the context of sustainability. The big data analytics processes targeting another kind of decision-making related to the improvement and change of practices and policies. Such processes pertain to urban planning, design, development, administration, and governance.

7.5.2 Description and Illustration of the Proposed Analytical Frameworks

The first framework is shown in Fig. 7.1 and the second framework in Fig. 7.2. Each of which consists of a few different components and shared components (namely typologies and design concepts, urban systems and domains, urban big data sources, repositories, and storage facilities, and urban entities and their activities), with some slight differences illustrated by changing the color of the relevant components.

- Typologies and design concepts (Figs. 7.1 and 7.2). Compactness, density, diversity, and mixed land use as typologies in conjunction with sustainable transport, greening, and passive solar design as design concepts all constitute key strategies to achieve the required level of sustainability in the context of sustainable urban forms (namely compact city, eco-city, green urbanism, new

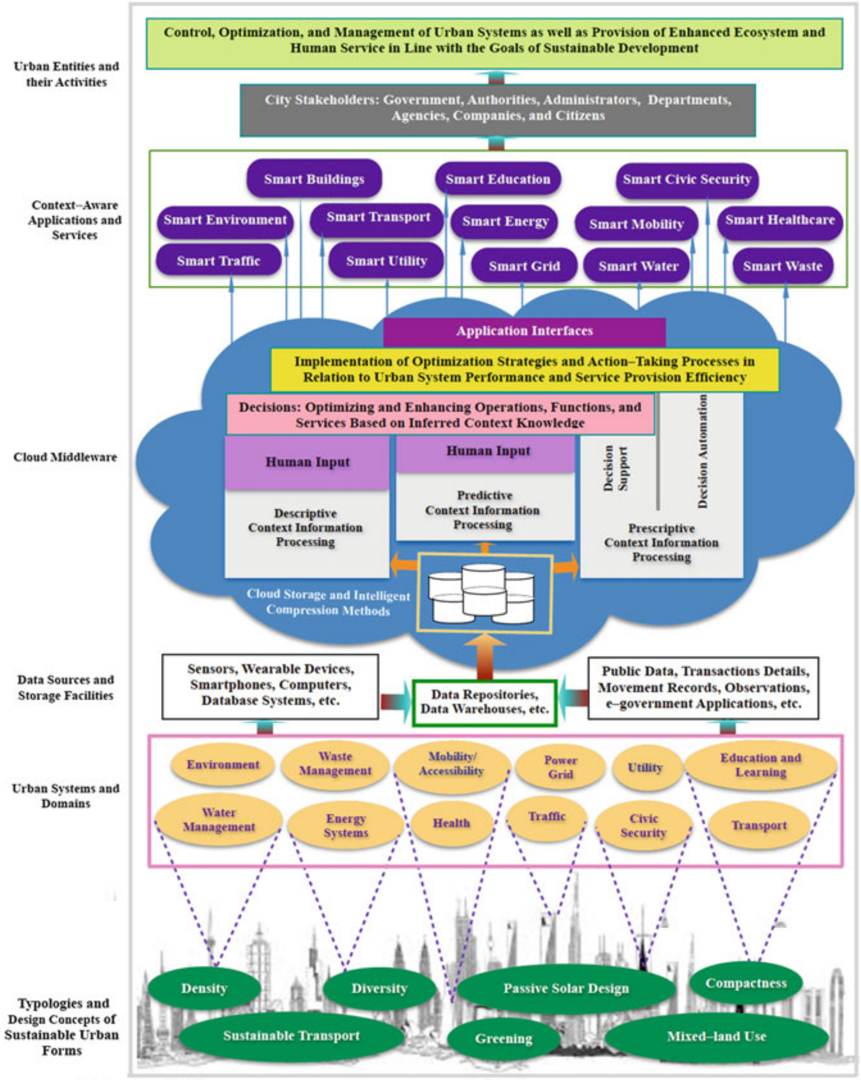

Fig. 7.1 An analytical framework for merging the physical and informational landscapes of smart sustainable cities based on big data analytics as a set of technologies and applications

urbanism, etc.) These urban components are to be supported by high standards of environmental and urban management. The sustainability effects of such typologies and design concepts include transport provision, travel behavior, mobility, accessibility, energy efficiency, pollution reduction, economic viability, life quality, and social equity.

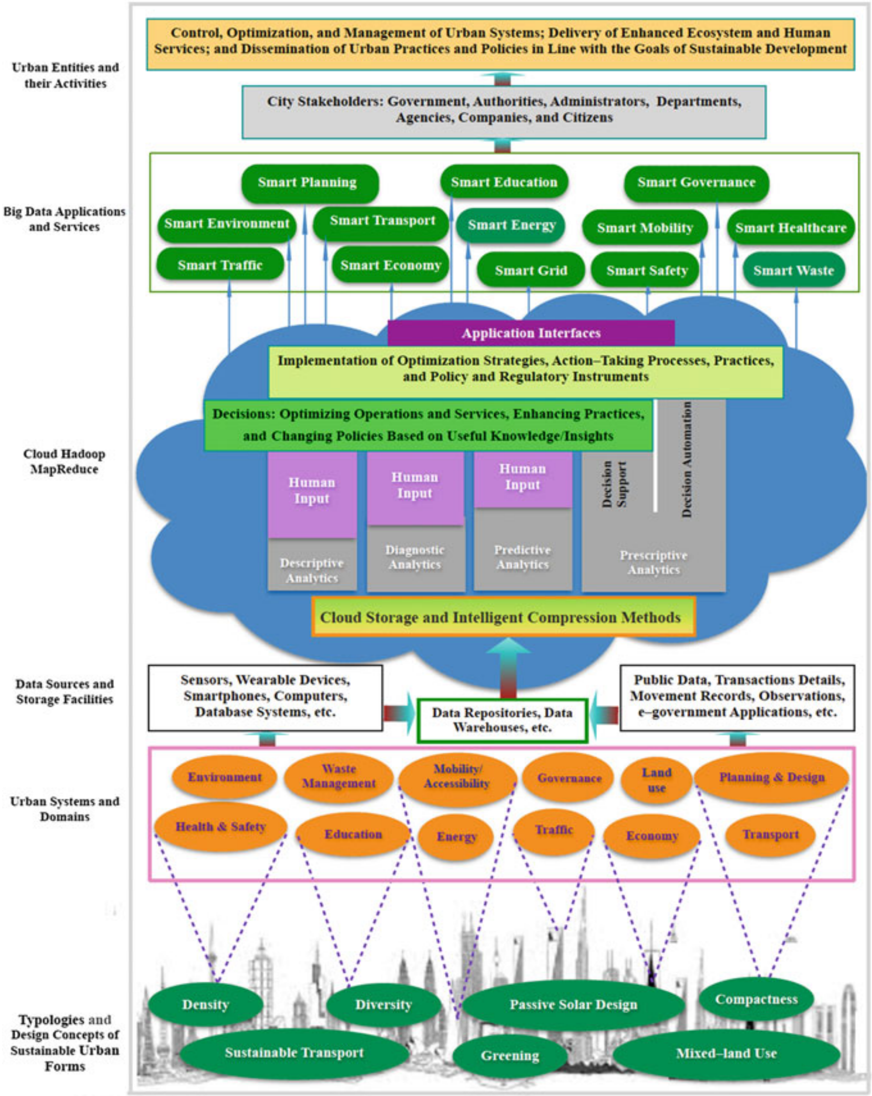

Fig. 7.2 An analytical framework for merging the physical and informational landscapes of smart sustainable cities based on context-aware computing as a set of technologies and applications

- Urban systems and domains (Figs. 7.1 and 7.2). These should function and be managed using advanced ICT, namely big data analytics and context-aware computing as a set of advanced technologies and their novel applications, as well as operate together with the above-mentioned typologies and design concepts. That is, smart sustainable cities should be—as forms of urban planning principles and urban design features for sustainability—monitored, understood, analyzed, and planned to improve their contribution to the goals of sustainable development on the basis of highly intelligent applications. Urban systems and domains constitute the main source of urban data, which are generated by various urban entities, including city government, city authorities, urban departments, urban administrators, individual citizens, academic institutions, and private companies (see Chap. 7 for more detail). They provide heterogeneous and colossal amounts of data as inputs for big data and context-aware applications. Urban data in their variety, scale, and velocity are invariably tagged with spatial and temporal labels, largely streamed from diverse sensory sources and stored in databases, generated routinely and automatically, and integrated and coalesced in data warehouses for use at the city-wide scale. Thus, this component involves different sectoral and cross-sectoral sources of urban data of varied types and sizes that are to be collected, stored, and retrieved for later processing, analysis, visualization, deployment, and sharing throughout the informational landscape in order to support urban operations, functions, services, practices, and policies.

- Urban big data and context information sources, storage facilities, and data categories (Figs. 7.1 and 7.2). This component is devoted to data collection, storage, and management. It involves data repositories, data warehouses, and silos of public data. For instance, warehousing as a technique used in the urban domain entails consolidation of data from several databases, which in turn are maintained by various urban units along with historical and summary information. Also, this component includes diverse sources through which data flow to the central city warehouse or main storage facility, including sensors, smartphones, wearable devices, computers, and database systems. These sensing devices and computing systems are used to collect and transfer data for retrieval, processing, and analysis using cloud computing solutions. Database management systems are used to maintain urban data of large-scale and diverse categories. Also, cloud-based storage can be fully virtualized—computer-generated version of the storage facility, and all devices are completely transparent to the urban constituents as users of the cloud, who can connect to cloud storage via the network. This enables such constituents to have storage equivalent to the entire storage capacity of the cloud. This feature attains linear expansion of performance and capacity. The added value of combining cloud storage with intelligent compression methods lies in, in addition to significantly reducing storage costs, providing the possibility of effectively storing all types of big data and context information belonging to the domains of smart sustainable cities.
- Cloud computing/fog computing infrastructure and Hadoop MapReduce platform for big data processing and management (Fig. 7.1). This component is dedicated to knowledge discovery/data mining and context information processes. As to knowledge discovery, the sub-processes involved encompass selection, preprocessing, transformation, mining, interpretation, and evaluation (see Chap. 4 for a description and illustration of these steps). As to data mining, the sub-processes involved include data understanding, data preparation, modeling, evaluation, and deployment (see Chap. 4 for a detailed description with

illustrative examples). These two processes are involved in the urban domains and sub-domains associated with sustainability, and are aimed at discovering new or extracting useful knowledge from large masses of data. The discovered or extracted knowledge involves intelligence functions and deep insights, and result from data processing and management performed by Hadoop MapReduce based on cloud computing. Such functions and insights are intended for decision-making, decision support, and decision automation. Intelligence functions are used for real-time and strategic decisions, depending on the application domain (e.g., traffic systems versus energy systems), in terms of control, management, and optimization. Deep insights are about the identified trends, gaps, and weaknesses pertaining to different urban systems and domains as to their performance in line with the goals of sustainable development, and thereby relate to urban planning, design, development, and governance in terms of improving practices, strategies, and policies.

- Cloud computing/fog computing infrastructure and middleware architecture for context information processing and management (Fig. 7.2). This component is dedicated to context information processing. Chapter 3 describes the processes involved in urban context recognition, including data collection, preprocessing, analysis, representation and reasoning, inference, decision-making, and action-taking. The inferred context knowledge is associated with intelligence functions directed for different purposes (decision support, automation of process controls and operative tools, and service delivery), and results from context information processing and management performed by cloud middleware. To generate inferences, reasoning algorithms (or reasoners) use semantic description logic, probabilistic logic, programming logic, rule-based logic, or an integration of these or other forms of logic to deduce high-level abstractions of urban contexts. Such algorithms are executed to generate new knowledge about the current situation pertaining to urban systems and citizens based on sensor observations and dynamic models, depending on the application domain. Context modeling and reasoning support collection, evaluation, and dissemination of context information in pervasive computing environments. Existing approaches to context information modeling differ in the support they can provide for reasoning about context information as well as in the computational performance of reasoning (see Chap. 3 for further discussion). Furthermore, input for context information processing as a set of computational understanding processes is acquired from data collected routinely from multiple sources and forms of sensors about various situations, events, environmental states, settings, and activities over time. In addition, at the communications level, pervasive computing in smart sustainable cities require ad hoc networking, adaptive access technologies, and advanced architectures to achieve seamless interoperability among wireless technologies (see Chap. 3 for further discussion). As regards to middleware, innovative architectures for pervasive computing will enable citizens and urban entities, sensors, and application servers to interact within existing physical service environments that require a well designed, standardizable architecture for the management of urban data associated with context information. It is expected that it will take some time before standard, interoperable context information management becomes achievable and deployable in the context of smart sustainable cities.

- Big data applications (Fig. 7.1). This component entails the diverse data-centric applications associated with sustainability in relation to diverse urban domains. One application usually involves many solutions pertaining to different sub-domains of each urban domain, depending on the type of the urban sustainability problem that is to be solved (see Chap. 4 for further details). To put it differently, data-centric applications entail system behavior, service delivery, practice enhancement, and strategy and policy change. This component involves the outcome of the implementation of optimization strategies, action-taking processes, practices, and policy and regulatory instruments. Therefore, it executes actions, provides services, disseminates practices, and promulgates policies according to the type of the decision taken based on the extracted useful knowledge, which involves different levels of human intervention (input), depending on the type of the analytics method adopted to deal with the urban sustainability problem pertaining to urban operations, functions, services, designs, practices, and policies. Accordingly, this component involves different decision and strategy support systems. In relation to practices and policies, the focus is on smart planning, design, development, and governance in terms of using big data analytics to enhance practices and policies with a more fine-grained representation of reality, to check which of them fail to make the needed or sought-after changes as regards to achieving the goals of sustainable development, and to act accordingly. As far as the system behavior and service delivery are concerned, the focus is on the control, automation, management, and optimization of urban systems as a set of operating and organizing processes and the efficiency and enhancement of ecosystem and human services respectively.
- Context-aware applications (Fig. 7.2). This component involves the diverse context-aware applications that proceed with executing actions and providing services according to the decisions taken based on the obtained inferences with respect to urban operations, functions, and services in relevance to the goals of sustainable development. As with big data applications, one context-aware application usually involves many solutions pertaining to different sub-domains of each urban domain, depending on the type of intelligence function needed with respect to urban systems and citizens. To put it differently, context-aware applications entail system behavior, service delivery, and decision support. This component involves the outcome of the implementation of optimization strategies and action-taking processes as to system performance and urban service provisioning. As far as the system behavior and decision support are concerned, they are associated with the control, management, and optimization of urban systems as operating and organizing processes of urban life, and concerning service delivery, it pertains to the enhancement of ecosystem and human services. It is worth pointing out that big data and context-aware applications provide different kinds of services and involve different kinds of

decisions, but do overlap in some of these two aspects in relation to urban domains in the context of sustainability (see Chap. 8 for further discussion). This implies that they share the same core enabling technologies.

- Urban entities and their activities (Figs. 7.1 and 7.2). This component depicts the diverse urban stakeholders that utilize big data technologies and thus avail of the related applications in relevance to different aspects of urban sustainability. These applications involve numerous benefits delivered to various urban entities, including government, authorities, administrators, departments, companies, agencies, and citizens in relation to their activities in terms of control, optimization, management, planning, development, governance, service enhancement, and so on. The ultimate goal is to contribute to the goals of sustainable development by employing advanced solutions to solve a wide range of challenges and problems affecting the long-term health and efficiency of smart sustainable cities and the quality of life of their citizens, thereby improving various aspects of sustainability.

7.6 Context Awareness for Physical Service Environments Within Smart Sustainable Cities

Over the next few years, mobile computing, sensing technology, pervasive information processing, and distributed middleware will combine to create a new generation of adaptively and proactively context-aware services (see, e.g., Bibri 2015a; Riva et al. 2008). Among such services are those that are compatible with the goals of environmentally and socially sustainable development in the context of smart sustainable cities of the future (Bibri and Krogstie 2017a, b). Context sensing infrastructures will be deployed in a wide variety of physical service environments (including medical centers, cultural facilities, education facilities, workspaces, train stations, airports, training/learning centers, roads, mobility trajectories, homes, meeting places, and buildings) across urban spaces to serve citizens through city government, authorities, departments, companies, and agencies. These infrastructures will use the wealth of information generated by sensors to better serve the needs of diverse urbanites and entities operating in the physical environment of smart sustainable cities. Physical service environments pertaining to the different domains of smart sustainable cities combine context awareness and pervasive computing and communication to deliver enhanced, highly efficient and usable services to urban constituents in ways that contribute to increasing sustainability performance, environmentally and socially.

With the deployment of wireless technologies on a hard-to-imagine scale and speed in the private and public domains of cities, opportunities for city government, authorities, departments, companies, and agencies to offer services to citizens moving within their physical premises with smartphones and portable computers will be enormous, especially in relation to sustainability. At the same time, emerging sensing, semantic interpretation, and hybrid modeling technologies enable the implementation of localization, presence, and personality services that are key enablers for the kinds of context-aware services of ubiquitous nature, to draw on (Riva et al. 2005, 2008) in the context of smart sustainable cities (Bibri and Krogstie 2017a, b). Moreover, a variety of low-cost sensors can nowadays easily be embedded in citizen devices and spread in urban spaces. Possible service providers of sustainably contextualized services include city government, urban departments, urban authorities, service agencies, universities, and hospitals across their associated physical service environments. Such environments provide services that are enhanced by context knowledge, e.g., physical environment (specific characteristics of urban space and citizen, the distance between citizens and objects located in urban space, and position and co-location of citizens), spatiotemporal setting, social environment, cultural setting, and so on. Physical environments across urban domains seamlessly integrate the services provided by the computing devices they entail, including sensors, embedded systems, and portable citizen devices as well as application servers running remotely on a grid (Riva et al. 2008). The major classes of services that physical service environments across smart sustainable cities can deliver include, drawing on Riva et al. (2008):

- Information provisioning: delivery of personalized, context-dependent content
- Physical environment awareness and control: access to information collected from
- sensors (e.g., video from cameras, events from presence sensors…) and control of the physical environment (e.g., open/close doors)
- Remote work support: access to personal data stores and services for users visiting the environment
- Collaborative work support: sharing information among users and service components present in the environment (e.g., by generating a context-based virtual shared data space)
- Sharing or leasing of networked devices and appliances.

The guiding vision of ongoing research in the field of smart sustainable cities is to make the physical landscape interact with the information landscape of applications and services pertaining to sustainability by collecting urban data from heterogeneous sensors in the environment and harnessing these data in an "intelligent" way. The implementation of this goal requires the development of a standardizable infrastructure, which supports the design and delivery of services, in which citizens in which the environment reacts intelligently to the needs and perceptions of citizens that interact with the surrounding environment (see Riva et al. 2008).

The once conjecture about technologies weaving themselves into the fabric of urban life has fertilized the embedding of ICT of various forms of pervasive computing into physical environments across the city, which respond to citizens's needs and actions. Most of the services delivered through context-aware service environments are services adapted to various subsets of citizen contexts, particularly the citizen characteristics, the citizen personality, the time, and the place of their use. In smart sustainable cities, context-aware services will evolve, enabled by wirelessly ad hoc networked, mobile, autonomous special purpose computing devices, providing largely invisible support for activities performed by individual citizens as well as collective actors across urban spaces and domains respectively. Moreover, it is expected that services with explicit input from and output to a variety of citizens and actors will be replaced by an informational and computational landscape sensing and monitoring the physical world via a huge variety of sensors and controlling it via a manifold of actuators (e.g. Ferscha 2003; Riva et al. 2008). Context-aware applications and services relying on context knowledge as inferences in relation to various aspects of urban life will have to cope with highly dynamic environments and changing resources in response to the challenges of sustainability and urbanizations, and will need to evolve towards a more implicit (adaptive and proactive) interaction with urban constituents in the context of smart sustainable cities. Pervasive computing environments in urban spaces are characterized by interactions among large numbers of miniature, heterogeneous, embedded, mobile, autonomous, active sensing and computing devices equipped with "peer to peer" mechanisms, which allow them to communicate with each other, and with the surrounding networking infrastructure and what this entails in terms of context-aware computing (Riva et al. 2005, 2008)

Typically, a context-aware service uses context information processing to, according to Riva et al. (2005, p. 75):

- Automatically deploy services for a user or control an environment
- Associate context information with other information, allowing subsequent access to this based on "contextual" search criteria (e.g., find all information relevant to this place)
- Personalize modes of interaction between the user and the service
- Select services relevant to the user in a given environment or situation (context-aware service discovery and provisioning).

Concerning the implementation of physical service environments within smart sustainable cities that can perform with context-aware capabilities, requires deployment of a sensing infrastructure; design and implementation of a context management architecture infrastructure for context data acquisition, distribution, and organization; deployment of wireless communication infrastructure for context data storage and coordination; and implementation and deployment of context-aware applications, which will be in the short term custom, specific to each service environment (e.g., Bibri and Krogstie 2017b; Riva et al. 2008). For a detailed example of a physical service environment for general purposes and the description of its characteristics (namely personal device, network architecture, service provisioning, service provisioning, sensing architecture, and modes of interaction between the user and the services), the reader can be directed to Riva et al. (2005, 2008).

Worth pointing out is that context-aware applications will, according to many technology analysts, prevail in the next few years, as physical service environments are deployed across cities by public and private organizations. This involves smart sustainable cities of the future, where the physical and informational landscapes will be merged, providing a fertile environment conducive to deploying and implementing technology-rich environments through which context-aware services can be delivered. It is becoming increasingly evident that smart urban environments, which can support sustainable living through intelligent, multimodal interactions and adaptively and proactively contextualized service provision, will be commonplace in the very near future, as new advances will emerge in the areas of sensors, actuators, and information processing systems.

Context awareness goes hand-in-hand with pervasive computing as to the provisioning of services to citizens. Thus, context awareness and pervasive computing architectures should be deployed in a wide variety of physical service environments throughout smart sustainable cities. Important to underscore is that research on context-aware services pertaining to the goals of sustainable development in the context of such cities should be tackled with a more interdisciplinary approach to inform and facilitate the acceptance and domestication of such services among citizens, which rely on machines monitoring their activities. Human-centered design (Bibri 2015a) as well as usability analysis and testing (e.g., Riva et al. 2008) are highly relevant to the design of context-aware services for specific and general purposes. The analysis of social and environmental impacts of context-aware technologies is also necessary and of high relevance in the ambit of urban sustainability (see Bibri and Krogstie 2016a, 2017a). Benefits should be weighted against drawbacks associated with privacy encroachments and abuses as well as security breaches and violations, as well as against environmental risks posed by current approaches to ICT design and development.

7.7 Constituents of the Analytical Frameworks: Urban Physical and Informational Landscapes

Sustainable urbanism has become as much a function of sensed, processed, analyzed, modeled, and simulated urban data as part of distributed urban computing as it is an organized, coordinated, standardized physical arrangement of the city and the underlying infrastructural systems, processes, functions, and services in terms of operation, management, planning, design, and development. Further, it is important to point out that the proposed frameworks are used here to further structure the components of the physical and informational landscapes of smart sustainable cities of the future. This is done through relating these components to those of the frameworks to ensure consistency.

7.7.1 Urban Physical Landscape

Urban systems and domains are among the main components of the physical landscape of smart sustainable cities. They are, to reiterate, the main source of urban data, which are generated by various urban entities. Urban domains encompass natural environment, built environment, waste and water management, land use, planning and design, health and safety, education and culture, energy, traffic, mobility, transport, governance, economy, and so forth. Urban systems include built form (buildings, streets, neighborhoods, residential and commercial areas, parks, etc.), urban infrastructure (transport, water supply, communication systems, distribution networks, etc.), ecosystem services (energy, raw material, water, air, food, etc.), human services (public services, social services, cultural facilities, etc.), and administration (delivery of services and provision of facilities to citizens, implementation of mechanisms for adherence to established regulatory frameworks, policy recommendations, various technical and assessment studies, etc.) (Bibri and Krogstie 2017a). At the core of the physical landscape of smart sustainable cities are the built form and infrastructural systems and what these entail in terms of typologies and design concepts, i.e., all strategies through which sustainable urban forms can be achieved. These are to be integrated with the informational landscape based on big data and context-aware ecosystems and their components in terms of tools, methods, models, and platforms in the design, development, deployment, and implementation of smart sustainable cities of the future. All urban systems and domains should operate and be managed and planned based on big data analytics and context-aware computing with these urban strategies in mind in order to improve and sustain the contribution of such cities to the goals of sustainable development.

7.7.2 Urban Informational Landscape

As regards to the informational landscape of smart sustainable cities, there is a large number and a wide variety of components to consider in this context, but our intention is to focus on the most relevant ones in accordance with the proposed frameworks. In addition to identifying and describing these components, we will cover relevant links between them as well as elucidate how they relate to the main components of the physical landscape described above. The idea is that the informational landscape comprises big data and context information as well as the technological architectures, infrastructures, and systems necessary for handling these data.

7.7.2.1 Big Data and Context Information and Their Urban and Technological Sources

This component is associated with the data sources and repositories component of the proposed analytical frameworks. Certainly, urban data are massive and come from heterogeneous and distributed sources. Some urban data are channeled by the public sector, including city governments, urban authorities, urban administrators, and urban departments, in the form of public databases (extended relational, document-oriented, and graph databases), sensor observations, details of economic transactions, education archives, healthcare records, healthcare information sent from citizens' smartphones and other mobile devices, e-government applications, and so on. Other urban data are channeled by the private sector-real-time details of citizens' movements and mobility via mobile calling records, details of purchase transactions, and citizens' interactions online via social media networking. Devices and systems involved in the process of urban data generation encompass sensors, smartphones, wearable computers, laptops, as well as data repositories, storage facilities, and data warehouses. To note, smartphones have become the sensory gateway to get different kinds of real-time data on citizens, and the amount of data being produced by or streamed from these mobile devices is daunting. In relation to this, big data are likely to "become associated entirely with routinely sensed data, especially as traditional datasets tend to be increasingly complemented by routine sensing, as well as crowdsourcing (where individuals enter their own data)." (Batty 2013a, p. 276) As far as context data are concerned, they are typically collected from various forms of sensors (see Chap. 3 for an overview of sensor types and sensing areas). Countless sensors are being widely deployed and networked in contemporary cities and embedded into every conceivable type of object, spread across the physical environment, attached to citizens, and installed along the trajectories they follow daily. This can generate unprecedented quantities of data that are useful for enhancing city services and heightening citizens' experiences of sustainable living.

Furthermore, public feedback data, which are intended to provide information to urban administrators on gaps in ecosystem and city services provisioning and needs for utility, healthcare, well-being, air quality, housing, security, safety, and other urban environment indicators pertaining to the quality of life, are channeled by both academic institutions and civil society organizations. Such data also involve a portion flowing from citizens through city authorities or urban departments. In this regard, new partnerships and alliances among different urban entities are necessary for the use of big data analytics and context-aware computing in the context of smart sustainable cities, especially city authorities are likely to lack data and computer scientists and hence must borrow them from academic institutions or industrial organizations. In particular, to facilitate data science, more data scientists are to be acquired by diverse urban departments. Otherwise, novel tools are needed for translating big data into easily understandable analytical approaches so that people working for the city government and authorities can handle data by running predefined forms of analytics.

7.7.2.2 Cloud Computing Infrastructure, Platform, and Software

This component represents a key part of one of the components of the two analytical frameworks. In recent years, cloud computing has attracted great attention and gained popularity worldwide, proliferating as part of the infrastructures of smart cities (see, e.g., Al Nuaimi et al. 2015; Khan et al. 2015) as an extension of distributed and grid computing due to the advance and prevalence of sensing devices, storage facilities, data/information processing platforms, pervasive computing infrastructures, and wireless communication networks. Especially, most of these technologies have become technically mature and financially affordable. By commoditizing services, low-cost (open source) software, and geographic distribution, cloud computing is becoming increasingly an attractive option (Kalyvas et al. 2013a, b). Additionally, cloud computing offer solutions to many challenges facing smart sustainable cities by facilitating big data and context information storage and providing the capabilities needed for data/information processing, analysis, and management for extracting useful knowledge and generating context knowledge. Therefore, cloud computing is the basic backbone for distributed urban computing involving the various functionalities of big data and context-aware applications in the realm of smart sustainable cities. As a combination of infrastructure, platform, and software (see Chaps. 2 and 3 for a detailed description), it entails a set of powerful machines in large data centers across distributed environments, which are used to deliver a variety of services and thus meet the needs of different urban constituents in terms of the use of big data analytics and context-aware computing tools, methods, techniques, models, and technologies in the context of urban sustainability.

Big data analytics and context-aware computing are both associated with cloud computing (e.g. Ji et al. 2012; Khan et al. 2015; Solanas et al. 2014; Riva et al. 2008), which is increasingly seen as the most suitable platform for highly resource intensive and collaborative applications or on-demand network access to a shared pool of computing resources (memory capacity, energy, computational power, network bandwidth, interactivity, etc.) (Al Nuaimi et al. 2015; Kramers et al. 2014; Voorsluys et al. 2011). This implies that computer-processing resources (e.g., databases, software programs, and mobile and fixed networks), which reside in the cloud, are virtualized, dynamic, and scalable. Therefore, only display devices for information and services need to be physically present in relation to various urban domains where diverse urban constituents can make use of systems and services associated with big data and context-aware applications. In view of that, supercomputers in large data centers as a distributed system of many servers are used to deliver services in a scalable manner as well as to enable the storage, processing, and management of vast quantities and varieties of urban data.

7.7.2.3 Hadoop MapReduce Architecture and Data Mining Software Systems

This component represents the data processing platform of the above-mentioned component of the first framework: cloud computing. There is a number of data processing platforms being used in different sectors for handling the storage, analysis, and management of large datasets (see Chap. 2 for some examples). The focus here is on Hadoop MapReduce platform due to the suitability of its functionalities with respect to handling urban data as well as to its advantages associated with load balancing, cost effectiveness, flexibility, and processing power. As stated by Singh and Singla (2015), Hadoop allows to distribute the processing load among the cluster nodes which enhances the processing power, to add or remove nodes in the cluster according to the requirements, and to make the homogenous cluster with various group of machines instead of the costly option of using one supercomputer, and to handle unstructured data. Another benefit of Hadoop is that it is free of charge for different commercial uses because it is an open-source architecture. There are different extensions of Hadoop, which are usually considered for comparison, including HadoopDB, Co-Hadoop, Hadoop++, and Dare (Singh and Singla 2015). Hadoop is a framework for data management on which MapReduce works as a programming model, and its functionality is based on batch processing: dividing the big task into small subtasks and then executing them in parallel. Numerous technologies (e.g., Apache PIG, Apache HBase, Apache Hive, Apache Scoop, Apache Flume, Apache Cassandra, Scribe, Apache Zookeeper, and many more) can be built on the top of the Hadoop system to form a Hadoop ecosystem along with HDFS to enhance the efficiency and functionality of Hadoop (Singh and Singla 2015).

While Hadoop is originally developed for use in the domain of business intelligence (e.g., customer buying behavior, advertisement targeting, user recommendation, retail, and search quality), its uses are increasingly being extended to include many urban domains in the context of smart cities and smart sustainable cities in connection with big data applications. For instance, Khan et al. (2015) propose a prototype to demonstrate the effectiveness of big data analytics, and implement it using Hadoop and Spark for the purpose of comparing the results in terms of the suitability of these two data processing platforms. Their study presents a theoretical and experimental perspective on the use of big data analytics in smart cities based on cloud computing. Their prototype analyses an open dataset to identify statistical correlations between a set of selected urban environment indicators of the quality of life, such as health, well-being, employment, air quality, housing, income, and crime. Another project using Hadoop for big data analytics in the context of a smart city is government city administration, where Hadoop architecture is used to, quoting Neirotti et al. (2014), "manage real-time analysis of high-volume data, develop a massively scalable, clustered infrastructure…for discovery and visualization of information from thousands of real-time sources, encompassing application development and systems management built on Hadoop, stream computing, and data warehousing" (Al Nuaimi et al. 2015, p. 7).

The big data phenomenon is associated with the open-source software movement, and Hadoop is an open-source architecture, to reiterate. It implements the HDFS (Hadoop Distributed File system) and MapReduce model. Using the master–slave architecture, HDFS involves storing, processing, and analyzing large datasets to extract useful knowledge. HDFS divide the large files into blocks in a standard way and store these blocks into a large cluster. MapReduce entails dividing the large task into small subtasks and then deal with them accordingly. It has four core components: input, mapper, reducer, and output, and their number vary based on the application domain. As explained by Fan and Bifet (2013, p. 3), Hadoop enables to write "applications that rapidly process large amounts of data in parallel on large clusters of compute nodes. A MapReduce job divides the input dataset into independent subsets that are processed by map tasks in parallel. This step of mapping is then followed by a step of reducing tasks. These reduce tasks use the output of the maps to obtain the final result of the job." Apache Hadoop is a software system that is designed for data-intensive distributed applications and used for storing, processing, and analyzing big data in Hadoop cluster. This homogeneous environment denotes that all the components (RAM, CPU, etc.) of the systems comprising the cluster share the same configuration (Singh and Singla 2015). The data systems are deployed as scale-out architectures on clusters of servers and storage (Khan et al. 2015). Another software system is Apache S4: a platform designed specifically for managing and processing continuous data streams in real time (Neumeyer et al. 2010).

Hadoop MapReduce architecture can run on the cloud. Khan et al. (2015) propose an abstract architectural design of cloud computing-based big data analytics in the context of smart cities. This is motivated by the guiding design principle of cloud computing as to reusing existing, well-tested, and reliable tools and techniques for big data analytics functionalities. The system architecture proposed by the authors consists of three layers for different functionalities: (1) the bottom layer comprises distributed and heterogeneous repositories and various sensors; the middle layer serves to map and link the resource data to support workflows to develop relations among data of different formats and semantics in the data repositories due to heterogeneous data sources, as well as to find scenarios; the top layer is an analytic engine which processes the data for application specific purposes, using the linked data available in the middle layer to submit queries, application algorithms to find specific information in the data repositories.

7.7.2.4 Middleware Infrastructure

Middleware infrastructure is associated with pervasive computing environments and distributed applications. These encompass UbiComp, AmI, and SenComp environments and applications. Middleware infrastructure (e.g., Azodolmolky et al. 2005; Soldatos et al. 2007; Strimpakou et al. 2006) plays a key role in the functionalities of complex distributed applications, including context-aware applications. Thus, context-aware computing, which is associated with UbiComp, AmI, and SenComp, requires middleware infrastructure to operate. This infrastructure can also run on cloud computing (Platform as a Service (PaaS) and Infrastructure as a Service (IaaS))—i.e., cloud middleware.

A middleware architecture developed by Paspallis (2009, p. 230) for context-aware applications "allows dynamic activation of context sensors and reasoners through a pluggable architecture, and it enables easy customization to various platform characteristics. The pluggable architecture allows the construction of context-aware applications where the context providers are not determined a priori. Rather, the applications only specify their context needs and, based on them, the middleware seamlessly binds them to dynamically available context providers. At the same time, the middleware monitors the dynamically changing context needs of the applications, and activates or deactivates the context providers accordingly." Thus, middleware is crucial for context representation, reasoning, and management (Bibri 2015a). Supporting context-aware applications necessitates a wide range of middleware components and services for they rely on processing, analyzing, and interpreting colossal contextual information collected from countless distributed sensors. With the evolving innovative solutions for operating efficiencies, facilitating networking development, improving data management, and easing development of and boosting interoperability between distributed applications, the intensive data processing, massive data dissemination, and advanced (sensory) data fusion necessary for building dynamic knowledge bases have become achievable (Bibri 2015a). This is of high relevance to the development and deployment of smart sustainable cities as to context-aware services and decision-making processes for improving different dimensions of sustainability. While the prospect of building middleware infrastructures of high magnitude, multi-layering, and complex distribution is now a clear prospect, lot of research is needed with practical and theoretical foundations in terms of engineering and design to apply context-aware computing within the context of smart sustainable cities. As noted by Bibri (2015a, p. 50), "there is a need to develop new middleware technologies for adaptive, reliable, and scalable handling of high-volume dynamic information flows for coping with the complexity of the unprecedented volume, diversity, and velocity of information flow, constantly changing underlying network connectivity, dynamic system organization, high sensitivity and real-time processing of data, and massive volatile and unpredictable bursts of data at geographically dispersed locations."

7.8 On the Implementation of the Analytical Frameworks

It is important to underscore that the proposed analytical frameworks—with their unprecedentedly merged specific urban and technological components—pertain to a model of the smart sustainable city that is not yet in use in any part of the world. There is no city that integrates the existing typologies and design concepts through which various models of sustainable urban form can be achieved with big data and context-aware technologies and applications. A city model combining ICT of the new wave of computing with urban design and planning, sustainability science, and sustainable development is still embryonic, i.e., in a rudimentary stage with potential for future development. A burgeoning body of research has started to focus on using advanced forms of ICT to strategically advance urban sustainability through providing efficient and useful services to citizens to improve the quality of their life, integrating and optimizing urban infrastructures, managing natural resources, enhancing planning and design practices, monitoring and improving policy outcomes, facilitating cross-domain collaboration, and embedding more technologies into spatial organizations and physical arrangements.

Further to the point, the model of smart sustainable cities of the future to which the analytical frameworks relate is still in the process of development, namely a framework for strategic smart sustainable city development. This is the core aim of a research endeavor being undertaken in the form of a Ph.D. program (see Chap. 11 for further details). This model presents a novel approach to smart sustainable urban living to the world, something to break through to the mainstream and thus to be replicated in different places across the globe. As discussed earlier, given that the field of smart sustainable cities is still in its early stages of development, there are no case studies to explore or investigate in relation to the proposed analytical frameworks. In fact, such frameworks are intended to be adopted and implemented after developing the model in question, which is currently under study.

Toward this end, however, it is necessary to put in place a cross-service domain system to ensure that access to the data from different urban domains is available at all times in terms of data input and result visualization by the different urban entities involved in the domain of sustainability planning or sustainable development in the context of smart sustainable cities. Prior to this, it is important to ensure that the diverse kinds of datasets pertaining to urban domains are open for use by the relevant city constituents in relation to big data and context-aware applications. Also, there are several issues that need to be discussed in relation to the implementation of the proposed analytical frameworks, in addition to technological, analytical, computational, and operational ones, which are of organizational, administrative, and regulatory nature. It is too early to delve into such issues in this chapter. They will rather be addressed after the development of the aforementioned model of the smart sustainable city. As to the technological, analytical, computational, and operational issues, the related discussion is partly covered in Chaps. 3 and 4 and partly in Sect. 7.7 of this chapter. An important point to add from an analytical and computational perspective is that Chap. 4 provides some guidelines that show how the different cross-thematic data categories can be integrated with respect to the use of big data in urban analytics. Chapter 4 also sheds light on what kinds of sustainability problems that the different analytics methods such as descriptive, diagnostic, predictive, and prescriptive are intended to solve in relation to various urban domains. Such methods are also implied in the Matrix in connection with the themes related to the typologies and design concepts of models of sustainable urban forms with regards to sustainability effects.

The proposed analytical frameworks involve a lot of processing, analysis, and management issues that are under scrutiny and investigation by the ICT industry, as well as under intensive research in academic circles (see Chap. 9 for more detail). One of the key aspects to highlight here concerns the complexity surrounding urban data in the sense of being stored with varying qualities, as well as having different formats, access methods, and resolution scale and standards (e.g., meta-data). Khan et al. (2015) provide some insights into how to deal with some of these issues in the context of smart cities. This also points to the progress that has been made thus far as to handling urban data processing, analysis, and management. Unlike smart sustainable cities, there are several smart city models that have been developed in recent years, some of which involve cloud computing-based big data analytics and context-aware computing solutions (e.g., Bibri and Krogstie 2017a).

In reflecting on the difficulty of the implementation of the proposed analytical frameworks in terms of big data and context-aware technologies and applications, the untapped potentials of related solutions are more likely than not to involve the technical potential and socioeconomic factors. For example, Bocken et al. (2012) provide a conceptual model for rapidly assessing the implementations difficulty of technological innovations. This can be used, in addition to the other tools being currently under research and development by the ICT industry and academic institutions, to assess the difficulty of the implementation of big data and context-aware technologies and applications pertaining to urban sustainability. As with all technological innovations, a successful implementation of such technologies and applications as part of the analytical frameworks is understood to incorporate not only their development and launch, but also their acceptance, domestication, and dissemination among diverse urban actors (authorities, administrators, departments, enterprises, urbanites, etc.). The conceptual model consisting of an evaluation of the implementation difficulty of big data and context-aware technologies and applications can be adapted to the objectives of this chapter with regard to the analytical frameworks in the context of smart sustainable cities of the future. This adaptation pertains to three different capabilities: the newness of (1) the big data and context-aware technologies, (2) the concept of big data and context-aware application, and (3) the extended network of urban actors. For example, newness, in this case, indicates whether the big data and context-aware solutions “are available and in use” or if they are “new to urban actors in the city”. This model can be a useful way of making a preliminary assessment while waiting for more advanced and specialized models that can be more pertinent in the context of the implementation of the analytical frameworks in terms of big data and context-aware technologies and applications. Such models are not available yet, and are expected to emerge as the research within the field of smart sustainable cities evolves and flourishes. For example, application of the conceptual model advanced by Bocken et al. (2012) and thus more detail on its capabilities with regard to the use of ICT solutions for energy reduction, the interested reader might want to look at a recent article by Kramers et al. (2014). In particular, this case highlights the use of this model to estimate the implementation difficulty (the sum of the three dimensions) of each of the suggested ICT solutions, which depends on the uptake of such solutions.

As to the identification of the low-hanging fruit of big data and context-aware technologies and applications in the context of urban sustainability, the opportunities have not yet been realized to any extent. Nonetheless, all the suggested big data and context-aware solutions present immense opportunities to advance urban sustainability through enhancing and integrating urban systems as well as facilitating collaboration and coordination among urban domains in terms of operations, functions, services, strategies, practices, and policies (Bibri and Krogstie 2016b). The low-hanging fruit that can be easily implemented are associated with energy, traffic, mobility, transport, education, and healthcare (e.g. Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Khan et al. 2015).

7.9 Conclusions

We are at the starting point of a new urban era where big data analytics and context-aware computing as a set of powerful technologies and applications will help us to discover useful knowledge and generate context knowledge for making a wide range of strategic, proactive, and knowledge-driven decisions within the various domains of smart sustainable cities of the future. These two advanced forms of ICT of the new wave of computing will allow us to monitor, understand, analyze, and plan such cities to improve their contribution to the goals of sustainable development. As rapidly growing areas of ICT, they are becoming ever more important to the development, deployment, and implementation of smart cities and sustainable cities alike, as they can enable them to leverage their informational landscape in the transition towards and advancement of sustainable development, respectively, by exploiting big data and context-aware ecosystems in ways that enhance their operations, functions, services, strategies, designs, and practices in line with the vision of sustainability.

Furthermore, the debate over the ideal or desirable smart sustainable urban form has just begun, and will undoubtedly continue in an increasingly computerized and urbanized world. In the meantime, the concept of smart sustainable urban development will evolve in terms of developing different models of smart sustainable urban form based on crafting new and making creative combinations of typologies and design concepts and principles using advanced simulation models—which will be effectively merged with the core enabling technologies of ICT of the new wave of computing to achieve the goals of sustainable development, as big data and context-aware technologies and applications become mature and widely deployed across urban environments. Therefore, the contemporary urban computing and ICT research agendas are of significance and salience to sustainable urban forms. But such forms need to be well suited to the requirements of such agendas, particularly in relation to the ubiquity presence and massive use of emerging and future ICT in urban systems and domains. Underlying such ICT are the various visions where technology in varying ways recedes into the background of urban life and becomes interwoven with urban processes, functions, services, strategies, designs, and policies, thereby being embedded virtually in all urban components and entities. Hence, it is imperative for the field of sustainable urban forms to extend its boundaries and look for new horizons beyond the urban form in order to further exploit and unlock the potential of its sustainability ambit by embracing technological innovation opportunities as too smart solutions and sophisticated approaches. In fact, research agendas of ICT of the new wave of computing must by means of offering novel applications pertaining to sustainability propel this field toward broadening its horizons and thus moving it beyond its current ambit of sustainability. Especially, the concepts and approaches developed for sustainable urban forms are associated with inadequacies, uncertainties, paradoxes, and fallacies (Bibri and Krogstie 2017a). Therefore, smartening up sustainable urban forms as urban development strategies are of high relevance and importance to achieve the required level of sustainability with respect to urban operations, functions, services, designs, strategies, and policies. This holistic approach holds great potential to rise to the challenges of sustainability and urbanization facing future sustainable urban forms.

The new digital transition increasingly fueled by ICT of the new wave of computing, on which many cities are increasingly engaging, is projected to unleash drastic transformational effects with respect to sustainability. One of the aims of this chapter was to examine and substantiate the real potential of big data analytics and context-aware computing to improve urban sustainability. This entailed integrating the big data and context-aware applications of smart sustainable cities with the typologies and design concepts of sustainable urban forms to achieve multiple hitherto unrealized smart targets or in ways that intelligently improve the contribution of sustainable urban forms to the goals of sustainable development. In doing so, this chapter offered a conceptual framework in the form of a matrix of smart sustainable urban form to help planners and scholars in understanding and analyzing how the contribution of such forms to sustainability can be advanced with the support of advanced ICT. This chapter focuses on three classes of the sustainable urban form (see Chap. 2 for a detailed account) given their distinctive contribution to sustainability. These classes are not mutually exclusive but rather compatible to a great extent, despite having overlaps among them in their concepts, ideas, and visions. This implies that there still are some key differences and characteristic concepts for each one of them. In view of that, compact city emphasizes density, compactness, and mixed land use; eco-city focuses on ecological and cultural diversity, passive solar design, renewable resources, urban greening, environmental management, and environmentally sound policies; and new urbanism emphasizes sustainable transport, mixed land use, diversity, compactness, and greening. Accordingly, different models use different scales of physical concepts, as well as emphasize some of such concepts over others. In practice, sustainable urban forms entail varied planning and design approaches. The question is, how such forms can be merged in terms of their design concepts and typologies with big data analytics and context-aware applications? This chapter outlines a distinctive set of three design concepts and four typologies as well as two classes of applications through which future settlements can evolve sustainably, and develops a smart sustainable urban form matrix that can contribute to improving the contribution of sustainable urban forms to the goals of sustainable development. These insights and perspectives are intended to inspire academics and planners as well as real-world cities to develop and deploy more convincing models of smart sustainable urban form and be specific enough in terms of the combination of the physical and technological components of such form. Regarding that, this chapter concludes that by using the relevant advanced applications in conjunction with the right scales of the design concepts and typologies, we can produce theoretically and practically different smart sustainable urban forms that respond to various ambitions of sustainability within different local, national, and international contexts.

According to the smart sustainable urban form matrix, this chapter additionally concludes that merging the physical landscape of sustainable urban forms and the informational landscape of smart sustainable cities holds tremendous potential to advance urban sustainability. Moreover, different scholars and planners may develop different combinations of design concepts and typologies along with advanced applications to achieve the fundamental goals of sustainable development. They might come with different smart sustainable urban forms, where each form emphasizes different physical and technological concepts. However, all should be forms that environmentally and socially contribute beneficially to the planet for the present and future generations. The viable smart sustainable urban form according to the design concepts and typologies of sustainable urban forms and big data and context-aware applications is that which effectively, meaningfully, and seamlessly integrate their underlying physical and technological components. Ultimately, smart sustainable urban forms aim to achieve different objectives or targets. The most prominent among them are decreased energy use, reduced waste and pollution, reduced travel distances and needs, efficient and sustainable transport, preservation of open space and sensitive ecosystems, design scalability, spatial proximity and connectivity, and livable and community-oriented human environments (Bibri and Krogstie 2017b).

In light of all the above, we conclude that ICT of the new wave of computing will provide many new opportunities to develop, operate, apply, and maintain diverse data-centric and context-aware applications that will effectively improve the contribution of sustainable urban forms to the goals of sustainable development. The underlying assumption is that emerging and future ICT will usher in information intelligence in nearly all the systems and domains of sustainable urban forms—i.e., an era of the omnipresence of computing resources and their always-on interconnection for providing powerful urban intelligence functions as advanced forms of decision support pertaining to the different dimensions of sustainability. This will eventually form a techno-urban ecosystem that is conducive to improving the long-term environmental and socioeconomic health and efficiency of sustainable urban forms and enhancing the quality of life of their dwellers.

Furthermore, this chapter intended to explore the opportunity of merging the physical and informational landscapes of smart sustainable cities to achieve the goals of sustainable development. This entailed proposing two different by related analytical frameworks in which the components of the physical landscape of sustainable urban forms and those of the informational landscape of smart sustainable cities are identified on the basis of a thematic analysis and then merged together to enable and support data-centric and context-aware applications across urban systems and domains in the context of sustainability. Specifically, the study identified two most influential technologies and their applications pertaining to models of the smart sustainable city as well as three design concepts and four typologies related to models of sustainable urban form. The proposed frameworks bring together a large number of previous studies into smart cities and sustainable cities, including research directed at a more conceptual, analytical, and overarching level, as well as research on specific technologies and their applications and urban forms and their configurations. They are intended to elicit fertile insights and provide new perspectives with respect to the amalgamation of big data analytics and context-aware computing as advanced areas of ICT in the context of urban sustainability. It also indicates which of their applications are of more applicability and relevance to which urban domain, and in which of such domain these applications may both be applied in terms of sub-domains. In addition, they are meant to stimulate research opportunities and endeavors. This outcome together with the detailed account of the physical and informational landscapes of smart sustainable cities provide the necessary material to inform relevant research and practice communities of the state-of-the-art progress in the field of smart sustainable urban development, as well as a valuable reference for researchers and practitioners who are seeking to contribute to, or working towards, the design, development, deployment, and implementation of smart sustainable cities of the future. Indeed, the intention is to align different urban stakeholders (scholars, researchers, scientists, architects, planners, developers, engineers, administrators, policymakers, decision-makers, etc.) and bring them on a common platform to operationalize and concretize the concept of smart sustainable cities to significantly advance the field in the context of big data analytics and context-aware computing.

As it has proven to be a worthy endeavor to apply big data and context information in urban analytics and planning to add a whole new dimension to sustainability in the realm of smart sustainable cities, more rigorous, intensive research within these two advanced ICT areas is highly encouraged, if not imperative. Especially, the emergence of big data and context-aware technologies and applications has provided numerous research opportunities for developing advanced solutions to some of the most significant challenges and pressing issues related to diverse spheres of urban society. Lastly, our hope is that this chapter will contribute to the development of more comprehensive conceptual and analytical frameworks needed in the current stage of research within the field of smart sustainable cities to stimulate their development and implementation and eventually mainstream the smart wave of urban sustainability.

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Chapter 8
Managing Urban Complexity: Project and Risk Management and Polycentric and Participatory Governance

Abstract The widespread dissemination of sustainability, the rapid urbanization of the world, and the global rise of ICT are the three most important global trends at play across the urban world today. They will most likely change the way cities can be managed and developed drastically. They are also rendering the tasks of urban management increasingly more challenging on many scales with regard to city development. This implies that the management of urban systems and what they entail in terms of operations, functions, processes, and services in the context of smart sustainable cities require complex interdisciplinary knowledge pertaining not only to project management and multiscale and participatory governance, but also to the administration of ICT and related computational and data analytics processes. These three urban management functions are particularly associated with significant risks and challenges that need to be managed and overcome, respectively, in the process of making decisions as part of the development of smart sustainable cities of the future. However, topical studies on project management, governance, and risk management approach these topics from a general perspective predominantly. From a somewhat specific perspective, the focus in this chapter is rather on these urban management functions in relation to smart sustainable cities as having distinctive characteristics with respect to both the ubiquity presence and massive use of ICT and what this entails in terms of information security risks as well as the complexity of multiscale and participatory governance structures and project management processes. This chapter intends to explore urban and ICT project and related risk management in the context of smart sustainable cities, as well as the various models of governance of their functioning and development. The emphasis in risk management is placed on both urban development and ICT projects as well as information security in relation to the use of cloud computing as an increasingly widely applied solution for big data and context-aware applications. As to governance models, we put emphasis on polycentric, participatory, and big data forms. This is deemed of particular importance to providing insights into workable, practice-oriented solutions for the management of the complexity of smart sustainable cities increasingly being sought by urban planners, strategists, policymakers, and decision-makers.

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Keywords Smart sustainable cities · Urban sustainability · Urban management Project management · Risk management · Multiscale and participatory governance Urban development projects · ICT projects

8.1 Introduction

The Urban Management Program (UMP) was established in the mid-1980 with the United Nations Development Program (UNDP) in the United Nations Human Settlements Program (HABITAT). Ever since, many major cities of the world have been striving to become hubs of learning and innovation in urban management while undergoing far-reaching changes in the aftermath of several political, social, and economic shifts, coupled with the rising challenges pertaining to sustainability and urbanization. The widespread dissemination of sustainability, the rapid urbanization of the world, and the global rise of ICT are the three most important global trends at play across the urban world today. They all remain unprecedented in their scope, magnitude, and transformational effects in history, and will most likely change the way cities can be managed and developed drastically. They are also rendering the tasks of urban management increasingly more challenging on many scales with regard to city development. This implies that the management of urban systems and what they entail in terms of operations, functions, processes, and services in the context of smart sustainable cities require complex interdisciplinary knowledge pertaining not only to project management and multiscale and participatory governance, but also to the administration of sophisticated ICT and related computational and data analytics capabilities. These three urban management functions are particularly associated with significant risks and challenges that need to be managed and overcome, respectively, in the process of making decisions as part of the development of smart sustainable cities of the future. There seems to be an agreement on what smart sustainable cities will achieve with respect to the well-being of citizens and the health of the environment. And urban management is as important as what such cities will attain in terms of enhancing governance, economic standing, and the quality of life of citizens, as well as in terms of creating environmentally friendly and sustainable infrastructures and facilities.

Urban management is a broad term covering a large set of functions, including planning, administering, regulating, and governing urban complexity. Managing urban complexity effectively will thus be one of the most challenging tasks faced by city governments for the twenty-first century, especially in the context of smart sustainable cities of the future. The underlying assumption is that the systems of such cities are very complex in terms of the related operations, functions, services, designs, and strategies, so too are their domains in terms of their integration, coordination, and coupling in the context of sustainability. Smart sustainable cities are complex systems par excellence (Bibri and Krogstie 2016), and plans for sustainable development alone cannot deal sufficiently with the deteriorated urban environment and the related issues that are derived from the unsustainability of urban systems and the unprecedented rate of urbanization. With their domains becoming more and more interconnected and their processes highly dynamic, they rely more and more on sophisticated technologies and innovative management approaches to realize their potential to achieve the required level of sustainability and to address the challenge of urbanization (Bibri and Krogstie 2017). The increasing urbanization implies significant challenges for city governments associated with different aspects of sustainability due to the problems engendered by urban growth (Bibri and Krogstie 2017; Neirotti et al. 2014). To disentangle these intractable problems requires innovative practices of urban management, as well as a more holistic perspective on problem-solving pertaining to different urban management functions. This entails advanced management skills for taming thorny problems that arise with sustainability and urbanization and for dealing with urban affairs whose solutions must be looked at from an interdisciplinary perspective.

To understand urban management in relation to smart sustainable cities, it is important to first understand the components of their fabric. In the forefront of urban management is, regardless of whether cities are smart, sustainable, or smart sustainable, the value-based management of socio-spatial transformation processes, in particular the physical, spatial, infrastructural, technological, environmental, social, and economic contexts. As urban settlements, smart sustainable cities are not merely a set of urban design patterns and (buildings, streets, neighborhoods, typologies, forms, etc.) and technological artifacts (big data and context-aware technologies and their applications). Their core function is to use and develop land, urban environment, and urban infrastructure as well as ecosystem and human services—in ways that ensure wise management of natural resources, efficient operation of infrastructures and facilities, optimal economic development, and high quality of life. Urban management is a combination of all streams converging together to ensure the performance of these functions. It is concerned with the development of urban living forms, in particular with the urbanization and sustainability of cities. As such, it develops, promotes, and strengthens innovative practices in urban politics, policy, and administration beyond traditional urban development. In the context of smart sustainable cities, the ultimate aim of urban management is to make cities more sustainable and thus livable, safe, resilient, and attractive places. Hence, such cities have the responsibility to manage so many complex aspects. To make things work, it is inevitable that all the above-listed functions work complimenting and supporting each other. In all, the management of smart sustainable cities entails identifying, describing, and analyzing urban spaces in all facets of the built environment in context with the various stakeholders and to activate stakeholder groups and integrate them into the projects and processes, as we will exemplify in relation urban development project management and urban governance, as well as to consciously shape future developments driven by the amalgamation of sustainability goals and smart targets. To achieve this, a variety of methods are typically employed, and then the results can be incorporated and implemented in formal instruments of planning and development, with a focus on the increase in value of urban areas. Therefore, urban management tasks are particularly important in urban planning and development processes.

The focus of this chapter is on three specific functions of urban management, namely project management, multiscale and participatory governance, and risk management given their prominence in the context of smart sustainable cities. These functions are also associated with many complexities and challenges. The focus is on the latest management theories in this regard, including theories on projects, plans, finances, risks, policies, and governance structures. Topical studies on project management, governance, and risk management approach these topics from a general perspective predominantly. From a somewhat specific perspective, the focus in this chapter is rather on these urban management functions in relation to smart sustainable cities as having distinctive characteristics with respect to both the ubiquity presence and massive use of ICT and what this entails in terms of information security risks as well as the complexity of multiscale and participatory governance structures and project management processes. The intent is to offer the knowledge to analyze the management of the complexity of smart sustainable cities, with a focus on specific functions deemed of high importance to urban development and ICT. To add, planning as a key urban management function has been discussed thoroughly by dedicating a whole chapter (5) to the topic, with a particular focus on big data analytics, data-driven decision, and sustainability.

This chapter aims to explore urban and ICT project and related risk management in the context of smart sustainable cities, as well as the various models of governance of their functioning and development. The emphasis in risk management is placed on both urban development and ICT projects as well as information security in relation to the use of cloud computing as an increasingly widely applied solution for big data and context-aware applications. Regarding governance models, the emphasis is on polycentric, participatory, and big data forms of governance. This is deemed of particular importance to providing insights into workable, practice-oriented solutions for the management of the complexity of smart sustainable cities increasingly being sought by urban planners, strategists, policymakers, and decision-makers. The main motivation for this chapter is to adapt the topics of project management, risk management, and governance to, and fit related functions with, the topic of smart sustainable cities, with the purpose of stimulating their development. Another motivation is to call for preparing future urban professionals and experts in different fields to face new challenges, and thus encourage them to seek new competencies. Especially, there is an increasing demand for specialized training and talent for administrators, leaders, project managers, and information security specialists. The primary purpose of this training and talent is to contribute toward the development of smart sustainable cities through various management functions. Indeed, across the globe, many universities and research institutions are responding to this demand by proposing study programs and training courses on specific and new aspects of urban management for diverse urban professionals and experts. The key issues being addressed are related to the most pressing problems of urban development worldwide with respect to sustainability and urbanization.

This chapter is organized as follows. Section 8.2 addresses various aspects and issues of urban development and ICT project management, covering conceptual, analytical, critical, and practical perspectives, while emphasizing the complexity of smart sustainable cities and providing some potential ways to deal with it. In Sect. 8.3, we introduce different risk functions, namely management, assessment, and analysis, and clarify the related conceptual ambiguities and differences. In it, moreover, we provide a detailed account and discussion of risk dimensions and issues, identify the significant risks associated with information security and urban development and ICT project management, as well as propose some approaches and insights into dealing with and mitigating such risks. Section 8.4 introduces and discusses different concepts and models of governance in relation to smart sustainable cities, and the main topics addressed includes polycentric governance, network governance, governance networks, participatory governance, and big data governance. Further, it identifies relevant research avenues in this regard. This chapter ends, in Sect. 8.5, with the enumeration of the main conclusions along with some reflections.

8.2 Urban and ICT Project Management

Projects are becoming increasingly the preferred model in the field of smart sustainable cities to drive, test, and implement change and innovation endeavors on several scales and across a multitude of urban domains, driven mostly by the need to respond to and eventually overcome the challenges of sustainability and urbanization. The focus in this chapter is on both urban and ICT projects as part of the development and implementation of smart sustainable cities of the future.

8.2.1 Project Management: Defining Characteristics, Types, and Approaches

The discipline of project management is concerned with initiating, planning, executing, controlling, organizing, and closing the work of a team to achieve specific goals and meet specific success criteria. Some of these phases are sometimes merged together, such as planning and executing or controlling and organizing. As information described in the project documentation created at the outset of the development process, the primary challenge of project management as a temporary endeavor is to achieve all of the project goals in relation to unique products, processes, or services within the given constraints (baselines which combined denote the performance measurement baseline) associated with cost, time, scope, quality, and resource, with the purpose to typically bring about beneficial change or added value, i.e., improving the performance of environmental, economic, and social sustainability within particular domains of smart sustainable cities. This change or added value pertains in this context of design, development, or ICT pertaining to the systems of such cities, namely built form, infrastructure, governance and administration, ecosystem services, human services, and so on, as well as to the set of novel ICT applications necessary for operating and organizing these systems. Smart sustainable cities also involve numerous operations (related to energy systems, transport systems, healthcare systems, etc.) which stand in contrast with the temporary nature of projects, as they entail permanent, semipermanent, or repetitive functional activities to generate products, processes, or services. These operations require, in practice, the development of distinct management strategies as well as technical skills (Cattani et al. 2011). Further, the secondary and more ambitious challenge of project management, especially in relation to large-scale projects, is to optimize the allocation of necessary inputs (resources) and apply them to meet the predefined objectives of the project. Worth mentioning moreover is that at the core of any project management is to foresee or predict as many risks, uncertainties, and other problems as possible so that the project is completed as successfully as possible.

The project management framework is used in a wide variety of domains spanning many industries, such as urban industry, ICT industry, and energy industry. While it can apply to any project in the context of smart sustainable cities, it tends to be tailored to accommodate the specific needs of different and highly specialized physical, infrastructural, spatial, environmental, economic, technological, and social activities across different industries. Many of the domains of smart sustainable cities (building, infrastructure, transport, mobility, energy, health care, education, etc.) can develop their own specialized forms of project management based on what they intend to deliver as final products, processes, and services. Such forms require specialized training and certification to respond to the requirements of the kind of the project that is to be managed. For instance, ICT industry has evolved to develop its own form of project management that is referred to as ICT project management, an area which specializes in the delivery of technological artifacts in the form of applications, processes, or/and services that are required to pass through various life-cycle phases, such as planning, design, development, testing, and implementation. In some highly specialized domains (e.g., integrated renewable solutions, transport engineering), project management focuses on the intricacies of research and development. In all, project management involves developing and employing repeatable templates that are specific to the domain of industry. This allows project plans to become very thorough, efficient, and highly repeatable, with the specific intent to increase effectiveness in terms of quality, cost, and time to deliver project results and thus achieve the intended objectives.

There are a number of approaches into project management as a set of interrelated activities, which tend to be applied based on their suitability to a given domain. There are also several extensions of these approaches based on the outcomes, activity, benefits, or value. Common approaches into project management include the following:

- Phased approach,
- Lean project management,

- Iterative and incremental project management,
- Critical chain project management,
- Product-based planning,
- Process-based management,
- Project production management,
- Benefits realization management, and
- Earned value management.

The iterative approach, for instance, as commonly adopted in ICT projects given its technical nature commonly encompasses analysis phase, design phase, development phase, testing phase, and implementation phase. In theory, these phases occur iteratively until the relevant goals have been attained. This pertains in the context of smart sustainable cities to the intended use of big data and context-aware applications with respect to achieving sustainability targets in relation to various urban domains (see Chap. 9 for further details and illustrative examples). However, regardless of the approach adopted, careful consideration must be given to the roles and responsibilities of all participating stakeholders, as well as to the overall project quality, timeline, and cost. Although users' involvement should continue through every project stage, it tends in the iterative approach to occur usually during requirements gathering and usability testing. This is, as research shows, more likely to negatively impact upon the outcome of ICT projects, especially when they are associated with sustainability aspects as a set of specified targets to be achieved. In this context, users of ICT projects (big data and context-aware computing applications) involve a variety of urban constituents, including citizens, administrators, operators, planners, designers, policymakers, and decision-makers (see Chap. 7 for further details). There is an urgent need for developing new project management methodologies that can illuminate the complexity of ICT projects and enable more stakeholders to be involved in the context of big data analytics and context-aware computing given the granularity associated with the development and implementation of the related applications with respect to concurrently increasing the contribution of the domains of smart sustainable cities to the goals of sustainable development.

8.2.2 Urban Development Projects

8.2.2.1 On the Management of the Complexity of Smart Sustainable City Projects and Stakeholders

With the wide acceptance and dissemination of sustainability and its application to urban planning and development, coupled with the rapid urbanization of the world, theory and practice of project management in the urban domain are dynamically evolving, embracing new theoretical and practical models as ways of carrying out and implementing a variety of urban development projects, programs, and initiatives. This involves the discipline of project management becoming increasingly tailored to accommodate the specific needs of different and highly specialized activities across diverse domain of the urban industry in the context of sustainability. Many of the domains of smart sustainable cities are developing their own specialized forms of project management based on what they intend to deliver as final products, processes, and services in relation to their development, to reiterate. Examples of urban development projects in this regard include, but are not limited to, the following:

- Transport systems engineering,
- Energy systems engineering,
- Building construction,
- Physical and spatial structures development,
- Mobility systems development,
- Distribution network systems development,
- Communication systems development,
- Water and waste systems engineering,
- Traffic systems engineering,
- Healthcare and education facilities development,
- Neighborhoods, districts, and intercity (re)development, and
- New-built, state-led, and super gentrification.

Sustainable urban development require that urban projects represent an all-encompassing understanding of the problems cities are facing, plan endeavors strategically and holistically, and deliver beneficial and enduring outcomes. Smart sustainable cities as emerging urban environments represent new circumstances that require new responses in relation to their development. One of these responses is to devise new ways of managing the related projects, irrespective of their scale, complexity, extension, and focus, by advancing and harnessing the knowledge and tools the field of project management provides in ways that enable to develop, implement, and realize urban development plans with a variety of environmental, social, economic, spatial, infrastructural, and technological values, thereby meaningfully contributing to the long-term goals of sustainably balanced urban systems. Smart sustainable city projects should aim to establish and emphasize socio-spatial transformation processes that contribute to value maximization of a variety of stakeholder groups in relation to various aspects of sustainability. This can be attained by value-based management of such processes as part of urban management, in particular the environmental, social, economic, spatial, infrastructural, and technological contexts. Hence, it is through embracing and integrating sustainability dimensions and developing innovative ways of activating and managing different stakeholders by involving them in the project phases and integrating them into the project processes in terms of width and depth, as well as by reconciling their perspectives, responding to their concerns, and including their values, that we could successfully manage the complexity of smart sustainable city projects and consciously shape future developments harmonizing sustainability goals and smart targets. Important to note is that stakeholders can be categorized according to different criteria in relation to how sustainability and smartness as a set of interrelated objectives are embedded in urban development projects.

Given the complexity, multidimensionality, and overarching nature of urban development projects, their management calls for a multi-stakeholder approach whereby stakeholder participation is prioritized and widened given its pivotal role in reshaping and enriching the project management complex to achieve the goals of sustainable development. This is of high relevance to the development of smart sustainable cities in relation to different aspects of sustainability associated with their diverse domains. Urban development projects differ depending on their complexity, scale, extension (time, cost, and quality), as well as on the diversity and multiplicity of the involved stakeholders. This typically influences on the initiation, planning, execution, organization, monitoring and controlling, and closing phases of project management, as well as on the strategic level of project performance. These phases are generally used to direct the use of human, material, and financial resources toward the accomplishment of the project objectives according to the sought quality and provided timeframe that eventually meet different stakeholder's expectations. While each urban development project is unique (and has to be considered as such) and also specialized, the common challenge of project management necessitates, in addition to an understanding of the broader context of the project, the ability to sustain the constant balance between the available resources, the sought quality, the provided timeframe, the different perspectives of stakeholder, and the constant management of the benefits delivered beyond the life cycle of the project. It is argued that projects management is not only about effective planning, communication, and evaluation to achieve anticipated outcomes (Alderman et al. 2005), but also about managing stakeholder involvement—the nature and organization of stakeholder participation (process design) and the way the process is managed (process management) (Edelenbos and Klijn 2006). Indeed, according to Newton (2009), one of the first steps in project management is to define who the stakeholders are and to analyze what their needs are. Stakeholders have a wide variety of social, cultural, educational, and professional backgrounds, as well as separate roles, functions, responsibilities, and interests within the execution/implementation of the project. Accordingly, the multiple involved stakeholders define urban sustainability and thereby the sustainability goals intended by specific projects through their lens (Ding 2008).

8.2.2.2 Urban Development Project Management—Functions and Rationalistic and Stakeholder Perspectives

Project Planning

No project can start, advance, and deliver results without planning. Planning is an essential aspect of project management. The planning process is used to gather understanding and support for the project. If effectively conducted, it can be instrumental in shunning or evading potential project failures. In this regard, planning should occur as a collective endeavor with the goal to create a sense of team spirit and encourage participation in the project early on. Erling (2008) strongly argues in favor of broad participation in the planning of the project. Thus, a guiding principle to project planning is to bring stakeholders on board and give them a say, as this creates better solutions or helps avoid solutions the stakeholders do not want, thereby steering clear of project failures. It is as crucial to provide a proper social and physical environment and adequate planning tools (Erling 2008).

Every project is planned to an appropriate level of detail during the planning phase of project management. From a rationalistic perspective of project management, there are different types of plans, including milestone, Gantt chart, or network plans (Newton 2009), in addition to plans detailing activities to be performed for each subgoal (e.g., milestone) as a way to monitor what has been completed and what remains to be done. In this sense, plans represent deliverables which can be completed in sequential, parallel fashion, or the combination of the two, depending on the nature and dynamics of the project being pursued. These deliverables also constitute the output of the execution phase. The core purpose of planning is to greatly plan time, cost, and resources adequately to estimate the work needed, in addition to effectively manage potential risks and uncertainties during the execution of the project. A failure to do so reduces the chances of successfully achieving the project goals. Project planning generally consists of the following tasks, according to (Kerzner 2003):

- Determining the approach to planning (e.g., Rolling Wave planning or level of detail)
- Developing the scope statement;
- Selecting the planning team;
- Identifying deliverables and creating the work breakdown structure;
- Identifying the activities needed to complete these deliverables;
- Networking the activities in their logical sequence;
- Estimating the resource requirements for the activities;
- Estimating time and cost for activities;
- Developing the schedule;
- Developing the budget;
- Risk planning;
- Developing quality assurance measures; and
- Gaining formal approval to begin work.

Additional processes may apply, as some areas are highly specialized or involve a certain granularity as to their execution. For instance, conceptual design of the operation of the final product in the case of new product development (e.g., ICT projects such as big data applications) may be performed concurrent with the project planning activities. Also, it is advisable in project management to plan for communications and scope management and identify roles and responsibilities prior to their assignment (project organization). Further, the execution phase following the formal approval to begin working with the project ensures that the planned deliverables are executed according to the project management plan. This phase involves, among other things, allocation, coordination, and management of human, material, and financial resources.

Moreover, it is advisable to include strategic planning in addition to tactical and operational planning. Strategic planning is about clarifying the project strategy in terms of how it goes about solving the challenges it might face as it evolves. Strategies are, however, often formulated with insufficient clarity and, as some views argue, are "basically symbolic in nature" (Erling 2008). In view of that, strategic planning may not warrant success. There is no silver bullet to the project success. It follows that the general perception that successful projects are well-planned projects is a myth (e.g., Erling 2008). Some views go even to contradict normal expectations. Blomberg (1998) maintains that the best-planned projects are the unsuccessful projects. Especially, projects change direction regularly. Yet, this does not necessarily mean that planning is of no help to avoid project failures; many empirical studies have showed positive correlations between project success and project planning. Dvir and Lechler (2004) found a positive correlation between the quality of the planning and project success. In their study, project success was measured as, among others, about having satisfied users and project partners. In most projects, stakeholder involvement is a determining factor for success. Otherwise success will, arguably, prove elusive. Projects require a broad view of stakeholder management. Hence, stakeholder involvement should start early on during the planning phase of the project. As a sound planning approach, Erling (2008) suggests and stresses the importance of a tiered planning. This entails promoting political embeddedness among stakeholders, building scenarios, and lobbying support for the project (Blomberg 1998).

In addition, it is argued that the best-planned projects are unlikely to be successful because they generate disagreement and disputes among the involved stakeholders due to the contingencies—unplanned events and eventualities—that emerge in real-world situations, especially in relation to complex projects, such as sustainable urban development that entails unquantifiable values and goals. In relation to this argument, unsuccessful projects pay rigorous attention to detailed planning, which may negatively affect stakeholder agreement (Erling 2008) and waste energy (Erling 1996). Regardless, it is important to involve a wide range of stakeholders in the very early stages of the project planning because wide participation widens the scope of available expertise, creativity, and experience. This consequently avoids project failures or benefit shortfalls. Stakeholder's involvement is a salient factor for success; otherwise success will prove uncertain, to reiterate. Smart sustainable cities as a set of urban development projects taking place in different temporal and spatial contexts require the recognition of the influence of the various stakeholders they can have on the pursued projects.

Project Organization

The organization function of project management entails assigning functional roles and responsibilities to the team members as internal stakeholders via a Responsibility Assignment Matrix (RAM). Entailing a division of work and delegation of responsibilities for task execution among team members, project organization should focus on team spirit in task performance in the most efficient way. To be effective, project organization should balance between action organization (task perspective) and political organization. Erling (2008) points out that it could be wise under certain circumstances that a project takes on the role of a political organization. This is indeed of high relevance to all urban development projects given their complexity and scale. Besides, no project manager is likely to get far without knowing how to behave (organize) like a politician (Pinto 2000). As to action organization, for a project is a collaborative effort by team members working together toward a common goal, a RAM is a valuable project management tool to face the challenge. It should be devised in a way that clarifies responsibilities—functional roles of the team members. This is a crucial aspect of project organization. Clear responsibilities tend to have an impact upon the project performance and effectiveness. Responsibility involves, according to Erling (2008), two components: task responsibility, which denotes accepting responsibility for executing a specific job, and outcome responsibility, which is about accepting accountability for performance (the way the work is carried out) and results achieved—completion of the job as agreed. The author recommends that three levels be considered in connection to accountability: strategic (principal) level, tactical (milestone planning) level, and operational (activity) level. The former involves the division of responsibility and accountability between the base organization and the project, the second among project team members to achieve approved milestones, and the latter for project activities. As to the project manager, he/she fulfills his/her task responsibility by delegating responsibility for task among team members, and the outcome responsibility by checking that the work is progressing and done satisfactorily (Erling 2008). In addition, by being a specialized organization—focused on a single objective, action organization results in streamlined organization, as it pursues action rationality, and with it the organization develops a strong belief in its capacity to achieve and generate results (Erling 2008).

However, a project is likely to attract contrasting views, since it is a coalition of stakeholders. Here political organization comes into play. As stakeholders' views are an important element of the project, it is effective for the project to grow into a political organization as well. Given that urban development projects are inherently a coalition of external stakeholders whose views are seen as contributory to the planning and outcome of the project, they tend to take on the role of a political organization whereby contrasting views—complementary or conflicting narratives—attracted by the project goals can be constructed, deconstructed, negotiated, and elaborated. Failure to do this, the excluded stakeholders might take collective action to hinder, block, or slow down the continuation of urban development projects. Regardless, urban development projects are expected to encompass various values and goals in terms of sustainability in this context, and thus must be able to build on the experiences and resourcefulness of the involved stakeholders. In the light of the ongoing institutional change of urban market liberalization, new interest groups and stakeholders are on the rise (Lehrer and Laidley 2008).

Erling (2008) strongly argues in favor of broad participation in the project organization. Political organization necessitates such skills as influence and negotiation, which are particularly consequential to resource the project. Especially influence a process by which a project manager can seek to persuade or bring stakeholders around to his/her own points of view. Negotiation is understood as a situation where all types of ideas from all stakeholders count regardless of how they emerge. It is about negotiating "man-days…winning the soul of potential team members…realizing energy, initiative, commitment." (Erling 2008, p. 176) Stakeholders approach the project from different angles and tend to have different agendas and priorities. "It is therefore important to know how to be a successful persuader", and to persuade is to demonstrate insights and know-how, present rational plans, be logical and argumentative (Erling 2008). In all, it is useful to undertake the role of political organization. Projects must be able to build on the views and ideas of everyone involved. A project manager prepared to act hypocritically at times is a difficult balance but essential nonetheless; besides, projects are partly action (rationality) and partly political organization. As some parts of an organization cannot be understood from a rational perspective (Weick 1975), organization often exhibit this type of duality (Brunsson 2002), but they are also expected to encompass various values and run an effective operation. The dilemma that "if the project tries to carry out one type of work satisfactorily…, it risks ignoring other works (such as maintaining considered, balanced relations with stakeholders with different views)" can be solved through managing politics and actions as separate topics (Erling 2008). This implies that the project organization need to be action oriented in some cases and politically oriented in others. The project consists of what is known as "loosely coupled systems" (Weick 1975). In this regard, "both systems affect each other, but retain their own identity as separate entities." Erling (2008, p. 158).

Project Monitoring and Controlling

The monitoring and controlling function of project management consists of identifying potential problems in a timely manner and taking corrective actions, when necessary. The project is evaluated using several instruments to monitor and measure its health. Requirements tracing approach is used in this regard to trace requirements from their initial entry, through each of the phases, to delivery—that is, the project evaluation is carried out with reference to the project goals defined at the initiation phase of the project. This ensures that project performance is monitored and measured regularly to identify deviations or variances from the project management plan. Accordingly, the implementation of the controlling function reinforces the defined performance and goals. Fulfillment and implementation of the tasks of project controlling (Becker et al. 2003; Schlagheck 2000) can be achieved by applying specific methods of project controlling, such as investment analysis, milestone trend analysis, cost–benefit analysis, value benefit analysis, and risk profile analysis.

Monitoring and controlling includes the following tasks, according to Lewis (2000):

- Measuring the ongoing project activities (where we are);
- Monitoring the project variables (cost, effort, scope, etc.) against the project management plan and the project performance baseline (where we should be);
- Identifying corrective actions to address issues and risks properly (how can we get on track, on time, and within budget again);
- Influencing the factors that could circumvent integrated change control so only approved changes are implemented; and
- Providing feedback between project phases so as to implement corrective actions to bring the project into compliance with the project management plan.

Usually, changes are introduced to urban development and ICT projects, and, therefore, their viability has to be reevaluated. It is important not to lose sight of the initial goals of such projects. The forecasted result may upon the accumulation of the changes not justify the originally designated timeframe and agreed budget as constraints pertaining to such projects. Thus, to have successful project management, it is important to monitor and track progress so as to stay within time and budget as frames outlined at the beginning of the project.

From a rationalistic perspective, controlling is finding the actual causes for possible deviations (e.g., performance, budget, quality, milestones, etc.) and proposing corrective actions. From a stakeholder perspective, deviations involve detecting the causes of changing process management and proposing adaptive or improvised processes of stakeholder involvement. In addition, since the final evaluation is about the beneficiaries of the project outcomes, it is important to ensure a balanced stakeholder involvement in order for these outcomes to be accepted by the involved stakeholder groups. Good outcomes are about the satisfaction of all the involved stakeholders, but also about an enrichment of ideas (Edelenbos and Klijn 2006). Besides, project management should understand and act upon the perception, experience, and expertise of stakeholders though establishing continual dialogue and collaboration for the purpose of developing trust and commitment that are essential to ensure successful urban development projects.

8.2.2.3 Inadequacies of Project Management Perspectives

Both rationalistic and stakeholder project management perspectives are associated with limitations. By focusing on the efficiency of planning, organization, and controlling to achieve predicted outcomes (Alderman et al. 2005), the rationalistic perspective emphasizes formal methodologies and techniques, an approach which is not fitted with sustainable urban development projects, as it falls short in considering stakeholder views, experiences, and expertise, thereby missing valuable ideas and inputs in the project planning and outcome. In their investigation of a service-led project, Alderman et al. (2005) conclude that a rationalistic perspective is inadequate to provide guidance to project managers and to explain actions and their justification in the project. Hence, they suggest what they label "the management of meaning" by providing interpretative frameworks in complex projects for their effective management, while arguing that project managers should go beyond bringing about consensus between competing narratives of stakeholder to include aligning effectively sense giving and sense taking. Sensemaking is a means to untangle the project management challenges in a newfangled way; it is, in complex projects, framed by the different narratives employed by different stakeholders, and a meta-narrative serves to meet the aspirations of all major stakeholders and reflect the overall vision of the project (Alderman et al. 2005).

Likewise, there has been very little faith in stakeholder analysis (Bryson 2004). Clifton and Amran (2011) argue that theoretical models of stakeholder are inefficient when looked at through the sustainable world lens. Indeed, the narrow stakeholder approach places much stress on understanding which stakeholder groups are important to the project. This implies that stakeholder groups impose different power, legitimacy, and urgency. This is at work in most urban development projects as temporary organizations. As a result, the outcomes of sustainable urban development project may not be a general response to all stakeholder groups—but guided by how important a few of them are to the project. This is not compatible with sustainable urban management where all stakeholders should have a stake in the project—seen as affecting or being affected by the project outcomes or objectives. Nevertheless, stakeholder approach is useful to ethical analysis because the idea provides a framework for assessing the impact of decisions on all relevant stakeholder groups, not just the project. Including many stakeholders will lead to a moral and ethical version of a common good to pursue (Bryson 2004). Although the broad stakeholder approach is espoused in urban development projects, the problematic issues (e.g., providing equal benefits for all parties) may still be active. When the public participation is important, the extreme individual views are not prevalent (Denters and Klok 2010). Bryson (2004) suggests that by an identification of the stakeholders through analysis techniques, it is possible to fulfill the missions and create public values. Overall, the stakeholder analysis models remain inconsistent with sustainable world criteria (Clifton and Amran 2011), which should be addressed in the development of smart sustainable cities of the future.

8.2.3 ICT Project Management

8.2.3.1 Managing Software Development Projects—Big Data and Context-Aware Applications

Smart sustainable cities involve a massive use of ICT in the form of advanced applications directed toward advancing their contribution to the goals of sustainable development. Therefore, ICT projects pertaining to big data analytics and context-aware computing as a set of novel software applications span over all urban domains, including transport, energy, mobility, traffic, building, waste, environment, health care, education, safety, and governance, in relation to urban operations, functions, services, designs, strategies, and policies. Here ICT projects are associated with all kinds of software applications that are to be designed, developed, deployed, and implemented as part of the ICT infrastructure of smart sustainable cities. The focus here is on big data and context-aware software applications given their relevance and importance to the management of the complexity of the systems of smart sustainable cities. Moreover, ICT projects pertain to a base organization or delivered to a client organization from the view of project management as a temporary endeavor. In either case, an organization entails such urban entities as governments, authorities, departments, agencies, enterprises, and so on.

Containing guiding processes for those who are concerned with ICT project management functions; project management methodologies include, but are not limited to, the following:

- Waterfall,
- Agile,
- Scrum,
- Rapid Applications Development (RAD),
- New Product Introduction (NPI), and
- Packaged Enable Reengineering (PER).

As the most popular software development methodology, the waterfall model is non-iterative design process. It is a sequential design process used in software development, and in which progress is seen as flowing steadily downwards through the phases of conception, initiation, analysis, design, development, construction, testing, production, instantiation, implementation, and maintenance. Also, Agile framework has gained footing in recent years as a specific type of RAD, and which is often implemented using Scrum. Scrum is regarded as a lightweight subset of Agile framework for completing complex projects. Indeed, Scrum works well for any complex scope of work, although it was originally formalized with broad applicability for managing and controlling iterative and incremental software development projects of all types, with focus on process adaptability, by rapid delivery of working software applications. The incremental and iterative work beats employed in Agile and Scrum are called sprints (or iterations) entailing small incremental builds. These are the basic unit of development and are restricted to a specific duration fixed in advance, which is commonly from 2 weeks to 1 month. All the aforementioned methodologies are relevant and suitable for the development of big data and context-aware applications in the context of smart sustainable cities. In 15 years' time, the predominant software development methodologies will likely have advanced enough that a detailed discussion in this chapter would be obsolete, while the general principles are the same as they were 20 or so years ago, and likely will change little over the coming decades. Besides, there are so many books out there that cover the aforementioned methodologies in more detail with illustrative examples for those readers who are interested in exploring them further, whether in relation to smart sustainable cities or other venues.

8.2.3.2 The Life-Cycle Model and the Issue of Stakeholder Involvement in ICT Projects

ICT projects emphasize the life-cycle model which tends to focus more on technical aspects and thus instrumental processes—codified knowledge, procedures, and techniques rather than on users as main stakeholders concerned with the project deliverables. A project life cycle from initiation to termination as one part of the project management framework is based on narrow conceptualization of ICT projects. This entails that ICT projects start from well-defined objectives and are framed around single discipline. Accordingly, it overlooks the human factors and complexity as to the ICT project deliverables, which may lead to unintended consequences. One of which is the failure or annulment of ICT projects. That notwithstanding, the model continues to prevail in ICT projects for it is believed to be well-suited for software development endeavors in which methodologies tend to dominate the project life cycle. Software development expects no thunderbolt solution to its various problems of complexity other than to adopt rigorous methodologies (Brooks 1986). White (1984) found a correlation between too much focus on the technical aspects and ICT projects malfunction. In a recent investigation of ICT project failures, McManus and Wood-Harper (2008) conclude that one of the major weaknesses in ICT projects is the total reliance placed on development methodologies, and "processes alone are far from enough to cover the complexity and human aspects of many large projects subject to multiple stakeholders, resource, and ethical constraints."

ICT projects should rather be concerned with change, as they are established to introduce new or enhance existing ICT applications and systems, which directly concern people. However, although PSO (person, system, and organization) development was originally used in ICT studies to summarize lessons from many ICT implemented projects (Erling 2008), the strategic use of PSO approach does not seem to be vigorously adopted in ICT projects. This is due to the fact that, as argued by Erling (2008), PSO projects entail complex deliverables since the results must be delivered in each of three areas: person, system, and organization. A lack of PSO application is manifest in a great number of ICT projects continuing to fail.

The adoption of PSO approach is of critical importance to big data and context-aware applications directed for advancing the contribution of smart sustainable cities to the goals of sustainable development given their complexity and the scope of their benefits. However, despite the counter claims made by ICT project managers and designers as regards to PSO, ICT projects still focus narrowly on the project technical outcomes and overlook human factors. In the event of the increasing demand for advanced technologies and their novel applications, especially big data analytics and context-aware computing, all the entities as both base and client organizations involved in smart sustainable cities have to consider both technical as well as nontechnical factors in order to achieve successful ICT projects—that is, ICT project deliverables must meet all the involved stockholders' expectations. It is with ensuring a balanced stakeholder involvement that deliverables are most likely to be accepted by the involved stakeholders. And quality assurance of project deliverables is measured against, among others, the similarity between deliverables' specifications and what is actually delivered.

A considerable proportion of deliverables pertaining to ICT applications fails to meet users' expectations, and ICT projects are subsequently canceled or abandoned, notwithstanding the attempt at making ICT project delivery more rigorous (McManus and Wood-Harper 2008). This is due to the lack of due diligence during requirements gathering. And a critical factor is the level of design as well as poor evaluation as to selecting software engineers with the right skill sets, and consequently, end users find it difficult to sign-off design work for related processes and models do not respond to their practical knowledge of the intended processes (McManus and Wood-Harper 2008), e.g., ICT-based operating and organizing processes of urban life related to the management of various urban systems. Users (citizens, urban administrators, urban operators, service agencies, etc.) when employed as a primary information source is an effective way of canvassing (surveying) user requirements and needs. It is important to access users' tacit knowledge (Erling 2008). Hence, it is critical to ensure an effective and continual communication between the ICT project team members and the end users. McManus and Wood-Harper (2008) found that among the symptoms of ICT projects failure include inadequate communication between the different team members working on the ICT project and the end users (stakeholders), no clear requirements definitions, and frequent requests by users to change the system. In all, the end users of the project deliverables are a particular important group of stakeholders in ICT projects. A review of current research on user involvement and development of ICT systems found positive outcomes (Kujala 2003).

However, user involvement can be a daunting challenge. It can complicate project work, escalate costs, and delay the project. User involvement appears to encumber the project with extraneous activities (Brodbeck 2001). Regarding other stakeholders, in particular in relation to the base organization, it is of significance to maintain "good and close relations with line managers, not least because they have the final word on the design of the deliverables they expect to receive." (Erling 2008, p. 249) This also helps synchronize among all the different departments within the organization to meet the challenge ahead. In the line of stakeholder thinking, by project leadership emphasizing effectiveness and flexibility, senior management support will reinforce the impact of good project leadership (Marble 2003) by approving a project priority-setting (Doll 1985). McManus and Wood-Harper (2008) conclude that leadership and stakeholder relationship management issues are not factored into ICT projects early on, and "are rarely discussed openly at project board or steering group meetings although they may be discussed at length behind closed doors…project failure requires recognition of the influence multiple stakeholders have on projects, and a broad-based view of project leadership and stakeholder management." Overall, there is a need for alternative ICT project strategies that should focus more on leadership and stakeholder relationship management criteria to realize and deliver successful ICT projects.

8.2.3.3 Project Strategy: Actions for Reaching ICT Projects Goals

As mentioned above, strategic planning in ICT projects is about clarifying the project strategy in terms of how it goes about solving the challenges it might face as it evolves. The management of ICT projects as temporary endeavors is typically based on a particular plan, i.e., a set of various actions that are to be executed to reach the project goals. These are concerned with the establishment phase of the project: why the project is set up, what it is supposed to achieve, and how its success is measured. The project mission (purpose), scope, schedule allocation, human and financial resources allocation, objectives, and deliverables to be produced by the project need to be developed and documented. The purpose of ICT projects pertaining to big data and context-aware applications is to enhance the operational functioning, management, and planning of the systems of smart sustainable cities in ways that strategically assess, advance, and sustain their contribution to the goals of sustainable development. This entails conceiving, analyzing, designing, developing, testing, evaluating, implementing, and maintaining a wide variety of software applications across diverse urban domains involving a number of urban entities or constituents, including city government, authorities, departments, enterprises, communities, and citizens.

The mission is typically broken down into hierarchical elements, i.e., a mission breakdown structure, to facilitate its analysis and clarification. It is meant to draw a detailed, comprehensive picture of what ICT projects (related to big data analytics and context-aware computing) are there to help bring into being; it should generate a shared understanding of the purpose of these ICT projects: improving environmental, social and economic sustainability in the context of smart sustainable cities. With mission breakdown structure, all the stakeholders involved get a clear idea of the purpose of the ICT projects in question, and a complete itinerary of everything affecting the accomplishment of the mission pertaining to sustainability. Indeed, any ICT project must start with a discussion of its mission, which relates to its meaning and expresses a desired future state, as well as its goals. The goals of the project are its deliverables that are to be handed at a set date, within a set cost frame, and to a set quality. Linking the desired results with the steps taken by the project is a crucial point in project management. The project deliverables provide this link between what the base or client organization wants and the project work. Set to be achieved by the project, the deliverables are to be provided prior to the completion of the project. As advocated by Erling (2008), they are to be delivered throughout the project, and their timely delivery and cost and quality determine whether the project has reached its goals and fulfilled its mission. The project goals are expressed as activities to be performed; an approach to goal setting that is not preferred, as Erling (2008) argues: what is crucial is what the activity brings about in terms of the desired outcome (new knowledge and skills), not the activity itself. In terms of PSO, the project goals are to be set for the three development areas: person, system, and organization: goals expressing the training of the involved people, goals describing the technical deliverables, and goals connected with developing the organization. In the context of smart sustainable cities, the former is associated with citizens, administrators, operators, and so on; the second with big data and context-aware applications as a set of completed milestones; and the latter with the urban entities involved in the mission of advancing sustainability. The goals set out what the project is supposed to achieve as objectives on time, within budget, and to the specifications. The project objectives include: completion of the project to the agreed date and within budget, provision of all deliverables identified to due date, fulfillment of all stated requirements of big data, and context-aware applications.

As far as the scope is concerned, it is defined such that all activities directly related to the purpose of the project are considered to be in scope, while those not directly related to the purposes are considered to be out of scope. Typically, the plan is said to only receive further baselines if a significant change in scope occurs. In terms of its evolution, the plan is considered to be a dynamic document, and thus can be updated regularly by default and on an unscheduled basis as necessary. In relation to communication, e-mails, SMS, and other communication channels can be adopted as a means to notify scheduled and unscheduled updates to the plan to all the participating stakeholders in the project according to the reporting plan.

8.2.3.4 Project Management Functions

Here, we will focus on the three main project management functions. These have been adequately discussed above in relation to urban development projects, and also apply to ICT projects given the generalizability of the project management framework, with some minor differences associated mostly to technical details. With that in mind, we will focus in this subsection on those aspects that pertain to the ICT industry as to the form of project management it adopts, with a particular emphasis on big data and context-aware application in the context of smart sustainable cities. The planning, organizing, and controlling processes and tools used in ICT projects tend to be more or less the same with a slight difference in detail depending on the scale, complexity, and extension of the project.

Project Planning

ICT project management involves milestone plans as well as plans detailing the activities to be performed. The latter can be used later to monitor and control what has been completed and what remains to be done. To set a global plan, the basic units of which are milestones, and a detailed plan is a key feature of project management. Typically, milestones occur when different threads of the project come together; they mark the finishing point of significant parts of the project or the transition from one phase to another. They represent deliverables which must be completed to move on to the next phase. According to Erling (2008), a milestone is about what the project is supposed to achieve by a preset date, and should describe a desired future situation; it refers to a point of time and looks forward to what the project should create. In ICT projects, major milestones and the associated completion identifiers can be identified. The common milestones (deliverables) of a typical software development project include, but are not limited to, the following:

- Baseline project charter;
- Project kickoff;
- System allocation;
- Software requirements specification;
- Software design specification;
- Project documentation;
  - Software project management plan;
  - Software test plan;
  - Software quality assurance plan;
  - Software configuration management plan;
  - Software verification and validation plan;
- Software programs (e.g., big data and context-aware applications);
- Software documentation (e.g., installation documentation, end-user documentation);
- Testing results;
- Implementation and installation of software applications; and
- Software training performed against the involved users (users, installers, maintenance team).

According to Erling (2008, p. 139), it is important to consider pursuing several milestones concurrently, as this can "help to incorporate activities for achieving several milestones in a single comprehensive plan." However, the above milestones have to be completed and delivered prior to the project closeout. Following their completion and delivery, closeout checklist items are all accounted for. Upon termination of the entire project marked by the objectives being met, a number of closure activities that can be performed before the project is considered closed. In addition, a post-performance analysis can subsequently be carried out, involving project participants and allowing data to be gathered about their performance and experiences, so that project processes may be tuned to improve performance on future projects.

As far as the detailed planning is concerned, it is associated with activity plan. It does not have to be in place until work on the milestone in question is ready to kick off. In software development projects, work activities are normally specified, and schedule allocation is illustrated by a network diagram with the critical path in a given color. Resource allocation is illustrated by a resource allocation table. And finally budget allocation is illustrated by a budget allocation table. It is to note that these tables (presenting the planning process) are very detailed. However, it could be a risky situation when the project gives plans more status than reality (Erling 2008). The map counts more than the territory. The focus should not on making a detailed plan for the overall project at the start of the project; the basic idea "is to defer the detailed planning until absolutely necessary" (Erling 2008). Also, it is considered better to draft many smaller detailed plans rather than preparing a single detailed plan. But it is reasonable to have a detailed plan for every milestone since the focus is on achieving milestones. Such plan is a critical means of communication between the project manager and the team members involved in completing a given deliverable (milestone). In relation to this, it is important to create a sense of team spirit and to involve a wide range of people in the early stages of the project, as participation widens the scope of available expertise and experience, to reiterate. In ICT projects, planning is as highly critical as emphasizing participation in it. This is instrumental to avoid project failures, as discussed above.

In addition, ICT projects account for risk management as part of planning. Maintained for the duration of the project by the project manager, a risk categorization table is established listing the current project risks, the indicators that determine the rating (high, medium, low) of the risk, and the current rating of the risk. It is distilled to produce major (diverse) risks, risk responses (the metric trigger value, the current value of the metric, the resolution approach, responsibility assignment, and expected resolution date), and weekly risk changes (the major risks posed to the project alongside the rank of the risk in the preceding week, the resolution approach, and so on). The related reports are to be reviewed at project status meetings on weekly or so basis. The project manager may add new risks to the risk categorization table at any time. Risk management is a crucial component of software development project planning.

Project Organization

As to project organization, roles and responsibilities are illustrated by a RAM, as mentioned earlier. A RAM of ICT projects would enumerate all the tasks to be performed, where responsibilities lie, and lists all the team members to be involved in the endeavor. In software development projects pertaining to big data and context-aware applications, a typical list of team members would include the following:

- Project managers;
- Requirement analysts;
- Programmers;
- Evaluators;
- Software architects;
- Software engineers;
- Validation engineers;
- Quality analysts;
- Configuration engineers;
- Technical writers;
- Database engineers;
- Training specialists;
- Installation specialists;
- Outside consultants;
- Executive and steering committees of the base or client organizations; and
- Data and computer scientists.

Normally, the above list is supported by a system of code to represent who from the team is involved in which task.

Project Controlling

ICT projects are evaluated using several instruments to measure and monitor their health. The focus is on performance, milestones, and goals in terms of status reports and project evaluation. Requirements tracing as a common approach is used to trace requirements from their initial entry, through each of the phases, to delivery. Relating all work effort to traceable requirements is intended to limit unnecessary work and ensure integrity of the software product requirements. Also, prioritization is used as part of requirements tracing in that when a requirement is entered into the system, it is assigned a priority, as follows: 3 = mission critical (product must have), 2 = important (should exist, but not absolutely necessary), and 1 = nice to have (should be present if time permits, but is optional). In conjunction with the above, a requirement change priority is used to rate the priority of incorporating change to the requirement. In terms of the change control of software product requirements, changes to requirements are considered based on their priority in light of different criteria, such as the extent of their impact to in-progress work products. Indeed, a project is required to take account of likely change in specifications during its life time, and the project manager must, in addition to monitoring status, assess current direction in the light of mission success criteria (Erling 2008). A matrix is used to illustrate the requirement-change priority a change receives, based on the requirement priority and change priority. In ICT projects pertaining to software applications, all requirements change requests are expected to affect project schedule and/or budget if they are introduced after the requirements phase is complete. Assessment of the impact of requirements changes on product scope and quality is also included and entails the leads involved in the current project phase. Assessments produced for each area must be communicated to the project manager who is to coordinate necessary resources to approve or reject the requirements change, as well as to negotiate increases in budget and schedule. Multiple requirements changes are discussed based on the requirement change priority.

In addition, the project manager should focus on the achievement of milestones and, in doing so, prepare project status reports and metrics, identify issues, investigate into their causes, and propose relevant solutions to address them and assist in the development of alternative methods for remedial action. Control is about finding the actual causes for the potential deviations and proposing corrective actions (Erling 2008). With these points in mind, in terms of schedule control plan, the project manager performs schedule control using the earned value management system and the critical path method to control the activities that are most crucial to the completion of the project on schedule. The critical path should receive special attention with respect to the completion of the project on schedule, and failure to complete these activities within their allotted time generates slippage of the entire schedule. To account for activities entering and leaving the critical path, the critical path is examined on biweekly basis. Activity completion status is reflected by the meeting of the sub-activity milestones, which are developed for each activity by the assigned resources as the depth of each activity becomes known. Milestones are communicated to the project manager who attaches a "% complete" value to each milestone, so that the progress of each activity can be understood. Milestones play a central role in the relationship between the project and the base organization, and represent important states through which the project should pass, as well as important results, in addition to having an intrinsic value beyond that of being checkpoints (Erling 2008). As suggested by Erling (2008), besides providing an account of which milestones have been reached, reporting should state whether anything in particular has occurred in the process toward achieving the milestones that might be of interest. The idea of the milestone report as a concise account from the project manager is that it should be able to see at a glance where the project stands. Analysis from the project manager should conclude with a proposal for actions that can be decided upon.

In addition, with the completion of each major milestone, all team members are expected to update their status and performance data, so that a milestone performance report can be issued. The information concerning how the sub-activity milestones are met by different participants is correlated with the "% complete" value attached to the milestone. And it is entered into the project schedule. Earned value measurements tool is used to monitor schedule progress, namely:

- Budgeted cost of work scheduled,
- Budgeted cost of work performed,
- Schedule variance,
- Schedule performance index,
- Estimated time at completion, and
- Critical ratio.

As a final point in schedule control plan, if schedule slippage becomes problematic, crashing the project using an established crashing process is considered as an option for bringing the schedule back in line with the overall project objectives. However, crashing may not be an integral consideration in some ICT projects should they be dependent on other projects or part of large-scale projects, and there is no stated cost advantage to completing the project sooner than the deadline.

As regards to budget control plan, the above steps and diagnostic instruments (techniques, methods, and tools) apply, in addition to a cost baseline, against which changes in cost are measured. It is created for the project once resource assignments are solidified. By and large, software development projects involve several diagnostic instruments focusing on project progress and expenditure, based on a comparison of current progress and expenditure with planned progress and expenditure. In this case, earned value and critical ratio (actual progress/schedule progress) (budgeted costs/actual costs) paint a condensed picture of current status (Erling 2008). But, "this type of status assessment suffers from a couple of weaknesses. All project activities are presumed known when plans are crafted… It is, moreover, a retrospective form of analysis. It looks back rather than anticipating the future. It is activity centered, not on future performance or goal attainment." (Erling 2008, p. 209) While status reports are an essential feature of project control, it is important to use reporting mechanism. The underlying assumption is that this mechanism emphasizes results and examines factors plausible to have some effects on the achievement of performance and goals.

As to quality control plan, different mechanisms are used to measure and control quality of work processes and software products, including audits that take place upon their request by the project manager. Regularly scheduled reviews of work products, defects, and other issues are tracked with a specialized tool that provides a central location for defect/issue logging and resolution status. Quality-specific metrics are collected and stored in database and tabulated along with an initial trigger value, which prompts investigation into the cause of the trigger being fired.

As regards to the reporting plan in software development projects, it is concerned with the involved stakeholders, their generic information requirements, the distribution of communication items, and the performance reporting data to be communicated during the project. Scheduled communication takes place directly with recipients of the item of communication. A stakeholders' general information requirements table consists of three elements: description (i.e., schedule, performance reports, status updates), format (i.e., paper, electronic, oral), and frequency (monthly, weekly, as created/needed). A distribution matrix illustrates which participants should receive which specific items of communication, and distribution locations include post, email address, extranet web site, and presentations. The project manager reports performance to plan using such metrics as earned value, requirement, quality, and risk. In terms of publication, the metrics can be posted to the web site on a biweekly or so basis, with special updates upon achievement of project milestones. The metrics, which fall into one of three categories: effort, reviews, and change requests, are collected by the project along with the methods that are used to collect them.

From a user perspective, the final question of the evaluation of ICT projects pertaining to big data and context-aware applications is about the users' opinion of the end results. In the context of smart sustainable cities, users are of different classes in terms of whether they operate, manage, govern, and plan various urban systems and the associated functions, designs, practices, and services (city government, urban authorities, urban administrators, urban departments, companies, etc.), or receive urban services (e.g., health care, education, utility, safety, mobility, and accessibility to facilities), including citizens, communities, and other urbanites. So, by ensuring a balanced user involvement and wide user participation early on, deliverables are more likely to be accepted by the involved stakeholders, and thus projects to find their way into successful implementation and use to serve their purposes: advancing the contribution of smart sustainable cities to the goals of sustainable development.

8.2.4 Urban Development and ICT Project Managers

In the domain of smart sustainable urban development, project managers are professionals that have the responsibility for initiating, planning, executing, organizing, monitoring and controlling, and closing a wide variety of urban development and ICT projects pertaining to construction industry, energy industry, infrastructure engineering, urban design, architecture, computing, telecommunications, and so on. They are accountable for accomplishing the goals set by the project. Their key responsibilities include creating clear and achievable project objectives; specifying the project requirements; and responding to the cost, time, quality, and scope constraints. In other words, they are in charge of developing, maintaining, tracking, and documenting project plans, schedules, timelines, communications, risks and uncertainties, resource allocation, scope, milestones, and other deliverables. Moreover, it is equally important for them to continuously reconcile the perspectives, respond to the concerns, and include the values of the contracting or participating stakeholders. To fully understand and adapt to the various internal procedures is crucial to adequately addressing the key issues of cost, time, and quality and to ensuring the realization of the project plans. Hence, it is critical for project managers to effectively communicate with internal stakeholders: cross-functional teams, employees, clients, end users, functional managers, and directors, as well as partnering with external stakeholders to assess and analyze issues and needs, and to facilitate decision-making while ensuring it moves the project ahead in the right direction. Effective facilitation, collaboration, and negotiation skills are therefore key to carrying out such duties successfully. Especially, in the urban domain, which is inherently interdisciplinary, project managers usually work with team members assembled from technology, industry, sustainability, and business resource pools, as well as with external experts, consultants, and other stakeholders. In all, project management is about successfully delivering outcomes in a timely manner, within budget, and to the sought quality.

8.2.4.1 General Requirements and Qualifications

Project managers must act independently and have strong organizational skills and strategic and operational acumen. Attention to detail in terms of quality, awareness of potential benefit shortfalls, ability to be resourceful within budgetary limits, and continuous follow-up within designated timeframes are key to bringing projects to completion successfully in the domain of smart sustainable urban development. Besides these requirements, high energy, perseverance, and willingness to go the extra mile to achieve large-scale project outcomes are necessary to achieve missions pertaining to sustainability.

In addition, as regards to detailed knowledge of project management information systems, ICT provides useful methodologies, techniques, and tools on how to manage projects. Empirical studies show widespread use of project management information systems (White and Fortune 2002). An empirical study carried out by Raymond and Bergeron (2008) shows that their use is advantageous to project managers in terms of improving effectiveness and efficiency as to planning, scheduling, monitoring, and controlling, and they have an impact on project management success, as they are instrumental in enhancing budget control, meeting deadlines, and fulfilling technical specifications.

Typically, project managers involved in smart sustainable urban development endeavors must have certification (e.g., PMI/IPMA) or equivalent training in project management methodologies for handling complex undertakings and programs, coupled with many years of hands-on project management experience and know-how in the relevant urban development or ICT domain. Essentially, they combine specialized and interdisciplinary knowledge to be able to handle projects dealing with multiple interrelated goals and diverse stakeholders. They should be able to juggle multiple projects, jump from one task to another, and handle multiple activities concurrently, as well as manage team members in a multitier environment. The related abilities enhance learning, self-sufficiency, creativity, and multitasking, which bring interest to, and enrich the performance of, project management functions. Moreover, strong interpersonal, organizational, written, and verbal communication skills are key to successfully carry out project management duties. Such skills are particularly of importance with regard to the management of stakeholder participation as a process. Communication facilitates collaboration, negotiation, and influence. It pervades every aspect of project work, necessary “in establishing mission and goals, to planning and organizing, and to build climate of trust.” (Erling 2008, p. 254) And as a leadership skill, it is instrumental in inspiring and motivating team members and thus enhancing team work performance and project outcomes. Better communication leads to higher team productivity (Erling 2008). Furthermore, project managers must demonstrate the ability to build rapport with technology, industry, academia, leaders, staff of all levels, and team members, as well as expertise in different leadership styles. This kind of knowledge is highly meritorious.

The above requirements are deemed necessary for achieving effective results with respect to designing, developing, deploying, and implementing functional and workable solutions on the basis of big data analytics and context-aware computing as advanced forms of ICT to advance the contribution of smart sustainable cities to the goals of sustainable development.

8.2.4.2 Professional Requirements

The claim that professional requirements in the technical areas of urban development and ICT are unnecessary in the management of the related projects is not relevant when it comes to large-scale, complex projects pertaining to the domain of smart sustainable urban development. Professional requirements facilitate communication and collaboration between project managers and the involved urban entities as both base and client organizations. Indeed, they allow project managers to understand and easily cope with the processes underlying the project planning, organization, and control, in addition to smoothly interfacing with numerous internal and external stakeholders and quickly forming productive and positive working relations with them, despite their varying technical backgrounds, interests, and competence levels. Drawing on Erling (2008), the idea is that a professionally qualified project manager will gain the confidence of the team members, which is necessary for him to do a good job. Professional qualification provides the skills to lead in a satisfactory manner.

It is useful to supplement the familiarity of the professional discipline involved with good leadership credentials. A study found that effective project managers are characterized by leadership abilities, but this does not suggest "that project managers believe technical expertise doesn't matter: they need technical know-how as well as good leadership qualities." (Erling 2008, p 105) In addition, having knowledge of various leadership styles is also important; it allows the project manager to act contingently on different factors.

8.2.4.3 Transformational Leadership and Transactional Leadership Styles

In the realm of project management, there is a variety of techniques and models that can be adopted to motivate the project team members so to ensure that the project key milestones and objectives are delivered and met, respectively. How to motivate a team tends typically to relate to the project manager's leadership style, such as transformational and transactional leadership. These styles are instrumental in team motivation: inspiration and incentives, respectively. Both of these styles have wider empirical backing (Erling 2008) and are not mutually exclusive (Bass 1999). Indeed, all leaders practice both styles (Erling 2008). They both have a positive effect on team performance (Lowe et al. 1996; Dumdum et al. 2002). Hence, reinforcing them lead to a better performance. Several scholars consider transformational leadership as more effective and beneficial in some types of situation than others (Lowe et al. 1996; Dumdum et al. 2002). Dionne et al. (2004) argue for transformational leadership based on the assumption that team performance depends on the quality of primary team processes that are consequential such as cohesion, communication, and problem-solving. A key factor of transformational leadership is inspirational motivation. This is crucial to facilitating shared team visions, which boosts team performance. Communicating the vision clearly and constantly helping team members to understand what the project manager wants to achieve. Drawing on Erling (2008), the project manager needs to clearly articulate and formulate his/her vision (mission) in a way that galvanizes and inspires team members, as well as to act and speak confidently, enthusiastically, and optimistically about the project. The clearer and the more appealing the vision, the more the project is likely to succeed. In addition, the project manager should empower team members to achieve the vision. Motivation can be improved by allowing more autonomy and encouraging self-confidence (Erling 2008). It is critical to express confidence and have faith in the team's ability of succeeding in the project endeavor. Research shows that teams perform better when they know that the project manager expects and trusts them to perform optimally (Erling 2008). It is also important to provide support, encouragement, and advice to team members. Additionally, the project manager should emphasize the importance of team work, genuinely care about team members, be an active listener with the heart and mind, walk his talk, and exhibit high ideals and strong ethical stance. In relation to this, Keller (1992) found that reinforcing the charisma and inspiration is the most performance boosting measure. Furthermore, the project ought to foster optimal state of mind among team members, as moods and emotions do affect team performance. In all, transformational leadership seems to fit most situations, but it is useful to add transactional leadership if the circumstances are right. Indeed, "it is not a question of either/or, but about which leadership style dominates in a particular situation" (Erling 2008, p. 246) As to transactional style, the project manager can alternately opt for incentives and conditional rewards to motivate team members. Also, team goal setting is of particular importance in the sense that clearly specified goals enhance the performance and productivity of the team. One meta-analysis study found that team goals had a clear impact on team performance (O'Leary-Kelly et al. 1994). With this leadership style, to have motivated team members, the project manager is required to provide clear ownership of defined roles and responsibilities, track the progress, follow-up with timely feedback, and hold the team members accountable for results. In his investigation of transactional leadership type factor, Keller (1992) found that it affects the ability to work to budget and schedule during the project early stages. Recognition and praise as intangible type of motivation are also important and should relate to how the team members help achieve the overall mission of the project.

8.3 Risk Management

Risk is associated with all kinds of the decisions that are made in and permeate everyday life, within a variety of settings, setups, and organizations. When a decision is to be made, one of two or more alternatives of action is to be decided on, and in deciding on one alternative of action, account must be taken on the possible events and states of the world as well as of the consequences implicit in each alternative of action for each possible event or state of the world. The unfortunate consequences subsequent to events or states constitute what risk is. Accordingly, the risk entails the possibility that an event or state will occur and adversely affect (be of a consequence for preventing) the achievement of the objective associated with the chosen alternative of action pertaining to the decision problem. Therefore, risk involves uncertainty, and risk management serves to control risk and thus uncertainty by means of different control components (e.g., control activities, event identification, risk assessment, risk response, and event monitoring), which result in different outcomes.

A commonly held view is that at the core of the term "risk" is the implication that risk is a choice individual or collective actors make depending primarily on the environment in which they live or on internal factors. From an organizational perspective, risk can be described as the unwanted consequences resulting from the possible effect of an event on some form of assets of an organization (Stoneburner et al. 2004). Such consequences can be either expected or unexpected/unforeseen, and it is their balance that actually defines and classifies the risk, rather than its size (e.g., Paquette et al. 2010). Generally, there are always some events and consequences that render the risk kind of challenging to understand and accept its associated cost, thereby the need for developing risk management programs. It is because of the failure of organizations in managing risks—i.e., being susceptible to the misunderstanding of the risk involved and the unrealistic benefits underlying their engagement in high-risk, yet potentially short-term rewarding, activities—that they create risk management programs in an attempt to identify, manage, and eventually mitigate risks to achieve acceptable rewards (Crouhy et al. 2006; Paquette et al. 2010). In the context of this chapter, risk management can be viewed as the process that allows to balance the operational and financial costs of protective measures and achieve gains in sustainability mission capability by protecting the ICT infrastructure as a set of architectures, systems, and data that support smart sustainable cities' missions with respect to achieving the goals of sustainable development or the required level of sustainability. In relation to this and with reference to cloud computing solutions, Fenz et al. (2014, p. 410) address, in a recent overview of information security risk management approaches, issues regarding "making the appropriate risk versus cost trade-off" by investigating the way in which information security solutions costs can "be factored in when determining the risk mitigation strategies," as well as evaluate existing "risk management approaches as to their capability of supporting cost-efficient decisions without unnecessary security trade-offs." However, Paquette et al. (2010) point out that most risk management programs are aimed at managing risk at all stages of ICT development, deployment, and implementation, as they are strongly linked to a standard life cycle of system development.

8.3.1 Definitional Issues of Risk Analysis and Risk Management

There are disagreement about the definition of and relation between risk analysis and risk management. One view sees risk analysis is an umbrella term for risk management, risk assessment, and risk communication. As to risk communication, it seems that there is some consensus as to what it entails. It is associated with the values of the targeted audiences, and involves how to reach them and to make the risk compressible as well as to relate it to other risks and how to predict their response to the communication situation. It is, like risk analysis and risk management, a complex cross-disciplinary academic field, and is aimed at enhancing collective decision-making related to organizational and societal goals. As to the diversity and multiplicity of the risk analysis and risk management definitions, it emanates from the fact that these terms relate to other concepts and approaches pertaining to organizations, institutions, cities, and societies at local, national, or global levels. One approach views risk management as one of the two main components of the notion of risk analysis. In addition, often times risk analysis and risk management are used interchangeably. Also, sometimes risk management involves risk assessment, and other times both concepts are differentiated or used separately.

According to Haimes (2004), risk management entails deciding on the approaches to pursue to deal with or tackle the identified risks, i.e., what to do about them, and risk assessment involves identifying, measuring, and gauging the probability and severity of risks in terms of the negative consequences. Drawing on Crouhy et al. (2006), risk management denotes the process of understanding, costing, evaluating, managing, mitigating, and avoiding unexpected levels of variability in the affected outcomes (financial, repetitional, managerial, informational, etc.) for organizations. In other words, it entails the forecast and assessment of risks together with the identification of procedures to minimize, avoid, or eliminate their impact. This involves “the activities involved in selecting and implementing mitigation measures to bring risk to an acceptable level within an acceptable cost,” where acceptability “must be defined based on a risk-reward framework which will encompass the value of a particular asset, and the consequence for its loss (both from a short-term and long-term perspective). Risk management is…the process of developing a risk-adjusted strategy that balances opportunity with consequence of actions” (Paquette et al. 2010, p. 246). Another approach views risk management as an umbrella term, where risk assessment is the component that is concerned with identifying, measuring, and gauging the risks, and risk mitigation is deciding on how to face or what to do to handle the risks (Hubbard 2009). Risk management is also perceived as the process of identifying, assessing, and prioritizing risks followed by coordinated application of various resources to maximize the realization of opportunities (Antunes and Vicente 2015). Hubbard (2009) conceives of risk management as the process of monitoring, controlling, containing, and mitigating the probability and impact of unforeseen or unfortunate events. In terms of prioritization as a subprocess, the risks with the greatest impact and the greatest likelihood of occurrence are of top priority as to handling, and risks with lowest likelihood of occurrence and the lowest impact are handled in descending order. In all, the whole process of risk management is defined as the impact of uncertainty on operational, managerial, financial, or strategic objectives, where the aim of the management of risk is to assure that uncertainty does not avert or distract the endeavor from such objectives. Regardless of the diversity of approaches to risk management, potential failures or unforeseen events drive actors (e.g., urban stakeholders) to develop risk management processes or apply risk management standards or programs to identify, monitor, control, mitigate, and manage risks to achieve some kind of rewards and maximize opportunities, e.g., in this context improving the contribution of smart sustainable cities to the goals of sustainable development with support of advanced ICT, including cloud-based big data analytics and context-aware computing.

8.3.2 *Digital Risks*

Digital risks have become a topic of importance in an increasingly technologized and computerized world, i.e., technologically advanced and evolving societies. Digital risks brought by the new digital transition from 2000s and onward pertain to information security and privacy. Included in any risk conceptualization in the private and public sector are the risks associated with ICT as to all kinds of infrastructures and related information systems and technologies. There are different taxonomies of risks associated with information security. One of which is that risks are tangible (e.g., unauthorized access, modification, destruction, theft, service unavailability, and infrastructure failure) and intangible (e.g., public access and confidence in ICT capabilities). Accordingly, system risks entail potential losses, abuses, misuses, breaches, violations, or failures in association with hardware, software, and data. Systems security risk denotes a situation wherein information systems and technologies are not protected against potential damage or loss in a sufficient way (Straub and Welke 1998).

Digital risks are about potential information security breaches and privacy encroachments, which are arising from ever-growing dependency on ICT and its embeddedness in everyday objects and environments and what this phenomenon entails in terms of data storage systems, data/information processing platforms, and online services. Privacy and security issues are a real dilemma in the realm of ICT. The challenge to determine the factors contributing to security and privacy has proven to be of complex nature. These two issues relate to, among other things, the sensitive and confidential information stored in diverse large-scale databases and digital systems pertaining to citizens, communities, and organizations. This requires high levels of security measures to prevent potential unauthorized use and modification of the stored information, in particular, due to malicious attacks, thereby protecting confidentiality and integrity (e.g., Bibri 2015). By the same token, it is important to prevent encroachments upon and abuses of privacy, thereby protecting privacy rights of citizens, communities, and organizations alike.

As more industries, institutions, and cities are providing and using services online, and also people are showing acceptance for this mode of service delivery, they are becoming more dependent on their ICT infrastructures and Internet operations, and equally people are becoming dependent on their mobile devices and Internet services. It is a major challenge for the new evolving role of digital risk management programs and assessment strategies for all kinds of organizations, including city governments, to enhance their operational performance and achieve their strategic objectives, thereby the need for understanding and strengthening the alignment of digital risks with the operational and strategic objectives of these organizations. Digital risk management and risk assessment are the next evolution in digital risk strategies.

8.3.3 On Qualitative and Quantitative Approaches to Risk Analysis

Depending on the application domain and its dimensions and how these intricately interrelate and dynamically evolve, risks analysis can be conducted using qualitative or quantitative approaches. This also applies to risk management with respect to measuring what to do about the risks. Qualitative risk analysis espouses words to identify and evaluate risks by providing a descriptive account of the potential risk, and qualitative risk analysis calculates numerical or numerically assess probabilities of the potential consequences of risks using mathematical or arithmetical values (e.g., Rausand 2011). Among the numerical units used in quantitative (probabilistic) risk analysis include time, currencies, lives, and so forth, and this approach aims to answer three questions: What can happen? How likely is it that it will happen? If it does happen, what are the consequences? (Kaplan and Garrick 1981). This approach to risk analysis typically results in a probability distribution over the consequences, and used in scientific and engineering domains. As a mode of inquiry, probabilistic risk analysis can be used to analyze engineering risks, e.g., big data analytical solutions, as well as health, environmental, and security risks. In, all, qualitative risk analysis is of a more rigorous nature and a better basis for making good risk management decisions compared to what is called pseudo-quantitative analysis approaches. These entail assigning numbers to the probability or likelihood of risks and their consequences, without building a mathematical model of the risk, using the risk matrix and categorization based on colors. However, pseudo-quantitative risk analysis has been a subject of much criticism due to the inaccuracy associated with ranking risks. In all, pseudo-qualitative analysis approaches are less rigorous than their counterpart and tend to provide a false sense of security as to managing risks (Hubbard 2009).

8.3.4 *Risk Management Methods, Challenges, and Principles*

The risk management approach tends to encompass common elements, performed, more or less, in a particular order and entails the techniques for measuring, monitoring, controlling, and prioritizing the risks, irrespective of the application domain to which such an approach is applied, whether concerning digital or other types of risks. As to digital risks, which relate to information security, in a recent review carried out by Fenz et al. (2014), a variety of risk management methods are identified and discussed in terms of their commonalities and differences and the common problems as to implementing them based on academic literature and industrial feedback. Most differences revolve around the distinction between rare, high-impact events and highly frequent, low-impact events, which led to the development of an approach to information security risk management consisting of these steps: identification of the requirements (asset values, threats, vulnerabilities, existing safeguards, etc.); analysis of threats, vulnerabilities and the scenario; risk measurement; acceptance test; and safeguard selection and implementation (Soo Hoo 2000). This approach became a de facto standard, although different process structures were provided afterward (e.g., Rainer et al. 1991; Straub and Welke 1998). This applies to other types of risks than digital ones, as the common risk management approach entails similar steps: identification and characterization of threats, assessment of the vulnerability of assets to specific threats, determination of the potential probability and consequences of risks on specific assets, identification of the measures to reduce or eliminate these risks, and prioritization of risk reduction measures based on a strategy. In addition to general risk management methods, several information security investment decision support methods have been proposed (Fenz et al. 2014). Fenz et al. (2014) derived a generic information security management approach based on the widely accepted and thus implemented information security risk management standards. As common problems regarding the implementation of information security risk management approaches, the authors found that these methods do not—based on the identification of "the fields of asset and countermeasure inventory, asset value assignment, risk prediction, the overconfidence effect, knowledge sharing and risk versus cost trade-offs"—explicitly provide or provide only limited "mechanisms to support decision makers in making an appropriate risk versus cost trade-offs on their own." Nevertheless, there are academic approaches as potential solutions to address the identified problems, which fulfill this need (Fenz et al. 2014).

Cloud computing providers, whether private or public, constitute entities that face the same challenges of information security risk management as other organizations. Like risk management methods in other domains, information security risk management approaches are associated with numerous challenges, which create hurdles to achieving sound risk management outcomes. In this regard, Fenz et al. (2014, p. 427) identified common challenges (and also provided potential solutions) pertaining to the implementation of information security risk management approaches, including the following:

- Identification of protected and countermeasure assets (e.g., customer data, production facilities, malware scanners, intrusion detection systems) as well as physical, technical, and organizational countermeasure inventory (e.g., locks, security doors, guards, firewalls, surveillance systems, backup policies, mobile device usage policies);
- Assignment of asset value (e.g., monetary loss, reputation);
- Failed risk prediction (e.g., unexpected areas, unknown risks);
- The overconfidence effect (e.g., risk estimations far too optimistic, limited time resources, stress);
- Information security risk management knowledge sharing (e.g., cost reduction in knowledge acquisition an security program development, innovation capability enhancement, security programs of higher quality); and
- Risks (e.g., not limited to financial loss, responsible for loss of image) versus cost trade-offs (e.g., the costs for countermeasures (including development, operational, and response costs), exceeding the expected loss of an asset, neglect of the cost-effectiveness of countermeasures).

Potential research avenues to address the different challenges facing the domain of information security risk management include methods for increasing the efficiency of countermeasure inventory and for determining the asset value, calibration tests for neutralizing the overconfidence effect, and knowledge sharing technologies for securely sharing information security-related knowledge (Fenz et al. 2014).

Important to add from a practical perspective, however, is that it remains problematic to deal with risk management issues due to the following:

- Risk assessment can be difficult to carry out, especially when it comes to large-scale ICT infrastructures and multi-actor-oriented decision-making and planning processes;
- Prioritizing the process of risk management to a high degree may hamper project launch or completion;
- Balancing and allocating resources employed to minimize or avoid risks with a higher likelihood of occurrence but lower impact versus a risk with higher impact but lower likelihood of occurrence tend to be more often than not mismanaged;

- Assessing and managing risks improperly could lead to time waste as to handling risk of losses of unlikely occurrence; and
- Allocating too much time to assessing and managing risks of unlikely occurrence can change the course of resources. This is anchored in the underlying assumption that allocated resources for managing and mitigating risks are perceived to be allocated for more profitable activities. Hence, it is argued that the best risk management approach is the one that minimizes spending as well as the negative impacts of risks.

8.3.5 Risk Sources: Tangible and Intangible Variables

There are just as many sources of risks as the domains to which risk management or uncertainty analysis can be applied. Examples of these domains include innovation, engineering, environment, infrastructure development, technology development, project management, public health and safety, transport, megaprojects, and unpredictable root-cause events. This implies that risk spans individuals, communities, organizations, cities, and societies. Commonly, risks involve two types of potentially unforeseen or uncertain events: negative events and positive events. As mentioned above, risk management is about developing a risk-adjusted strategy that balances consequence of risky actions with opportunities (Crouhy et al. 2006). Furthermore, as risk sources are classified and diversified according to the application domains of risk management, they can be located in managerial, infrastructural, technological, environmental, and physical assets as tangible variables, as well as in behavioral, cognitive, intellectual, relational, and social factors as intangible variables. It is argued that the interplay between assets and human factors of risk emphasizes the need to focus closely on human factors as one of the main drivers for risk management. These drivers emanate from the necessity to know how humans perform in challenging and fast-paced environments and in the face of diverse risks (Trevisani 2007). On this note, Trevisani (2007) states that “it is an extremely hard task to be able to apply an objective and systematic self-observation, and to make a clear and decisive step from the level of the mere ‘sensation’ that something is going wrong, to the clear understanding of how, when, and where to act. The truth of a problem or risk is often obfuscated by wrong or incomplete analyses, fake targets, perceptual illusions, unclear focusing, altered mental states, and lack of good communication and confrontation of risk management solutions with reliable partners. This makes the Human Factor aspect of Risk Management sometimes heavier than its tangible…counterpart.” Put differently, intangible risks are of a 100% likelihood to occur but they tend to be overlooked by organizations due to a lack of the ability to identify them compared to tangible risks. For instance, when there is a deficiency in knowledge or collaboration in terms of implementation in some situations, related risks materialize, adding to the application of ineffective operational procedures or processes by humans. These risks consequently affect several organizational aspects such as performance, cost-effectiveness, efficiency, service, quality, reputation, and so forth. Therefore, intangible risk management enables to develop immediate value from the identification and mitigation of risks. Some facets of many of the risk management standards developed by ISO, Project Management Institute, and the National Institute of Standards and Technology have been subject of much criticism for increasing the confidence in estimates and decisions and for possessing no measurable enhancement of risk (Hubbard 2009).

8.3.6 Cloud Computing and Information Security Risks

Many city governments have expressed the vision to explore, deploy, and implement cloud computing as a key component of the ICT infrastructure of smart sustainable cities of the future. However, there has been a growing recognition of the substantial risks and vulnerabilities posed by cloud computing solutions in the event of organizations, institutions, and cities rushing to such solutions to decrease costs and achieve service flexibility. Despite its numerous benefits (see Chap. 3 for more details), cloud computing presents significant challenges and poses many risks due especially to the ever-expanding range of accountability standards, namely data security regulations and data volatilities (retention requirements). Information security is one of the risks to consider when deciding to adopt cloud computing solutions (e.g., Kalyvas et al. 2013a, b; Neumann 2014; Paquette et al. 2010). It is not straightforward to implement cloud computing solutions for big data analytics and context-aware computing in terms of data and information processing platforms since their scale have many implications for security, adding to privacy, multi-tenancy, access control, and so on.

Despite its numerous advantages and bounties (e.g., Kalyvas et al. 2013a; Neumann 2014), cloud computing presents significant risks. Information security is one of such risks to consider when adopting cloud computing solutions (Kalyvas et al. 2013a, b), to iterate. The source of new information security lies in the scale of some of the clouds as large distributed systems of servers with few centralized controls, especially when it comes to the clouds that store all kinds of sensitive data (Neumann 2014). Here, the significance of the issue stems from potentially putting trust in untrustworthy entities. Therefore, cloud clients, whether citizens, organizations, or governments should evaluate information security risks associated with the use of cloud computing before making their decisions about this use, and ensure a level of realistic assumptions about their expectations of trustworthiness (Paquette et al. 2010), particularly when the sensitivity of the data is of critical importance. This entails questioning confidentiality, systems and data integrity, reliability, robustness, and resilience (Neumann 2014). In particular, governments and its departments and agencies must be practical enough to safeguard security to guarantee protection of all information. In addressing the tangible and intangible risks associated with the use of cloud computing in governments and exploring the level of their understanding by governmental departments and agencies, Paquette et al. (2010) argue that it is necessary to have a prudent and in-depth risk management program so to prevent unwanted consequences. The rationale is that it is difficult to fully govern and control cloud providers outside the governments, thereby the need for a thorough understanding of the involved risks and service agreement (Paquette et al. 2010). Regardless, the technological safeguards proposed thus far to mitigate security threats remain inadequate to eradicate the problem (Bibri 2015). Indeed, in relation to information confidentiality as one important category of security threats, while cryptography approaches can enhance confidentiality as well as provide a means to share the information using out-of-band cryptographic keys, they remain vulnerable to other categories of security threats, such as malicious deletion, unavailability of servers, invasive usage monitoring, loss of cryptographic keys, and so forth (Neumann 2014). In addition, cryptographic mechanisms in wireless and mobile ad hoc networks are seen to be susceptible to security attacks (Bibri 2015). Vulnerable moreover to misuse are schemes for recovery of lost keys such as backdoors, which can be used by insiders or external attacks (Neumann 2014; Fenz et al. 2014). Regardless, cryptographic approaches will continue to be used as a means for protecting personal data stored remotely and communications between devices and thereby for increasing security measures, notwithstanding their vulnerabilities as to intercepting information transmitted over networks (Bibri 2015). Indeed, as it is managed only by end users for remote information storage, cryptography raises issues relating to the trust of untrustworthy remote storage providers, in addition to allowing computations on encrypted information, without resorting to any form of information decryption (Neumann 2014).

Cloud computing brings significant risks, just as it provides significant values. Hence, governments and its departments and agencies must have the processes in place to effectively balance the benefits and risks associated with the use of cloud computing. Accordingly, Kalyvas et al. (2013b) provide a practical framework for managing cloud computing, proposing a number of specific recommendations in terms of information security risks, namely:

- Data—security, redundancy, ownership and use rights, and conversion;
- Insurance;
- Indemnification;
- Intellectual Property;
- Limitation of Liability;
- Implementation;
- Term;
- Terms;
- Warranties;
- Publicity;
- Exclusivity;
- Assignment;

- Pre-agreement provider due diligence;
- Post-execution ongoing provider assessment; and
- Negotiations.

For a detailed account of these recommendations, the interested reader might want to read the original article for gaining a better understanding of how the security and other issues arising from the use of cloud computing can be mitigated or eliminated.

In the context of smart sustainable cities, cloud clients need to focus on the security and control of their data as well as service availability and performance, as these central points can enable them to substantially mitigate the risks posed by cloud computing relationships (Kalyvas et al. 2013b). Only then can city governments identify opportunities and applications for cloud computing (e.g., big data analytics and context-aware computing) and implement them within the local policy frameworks, thereby avoiding unwanted or unforeseen risks that urban departments and agencies may encounter. A suitable governance structure in relation to cloud computing must be put in place and be constantly reviewed to manage an effective risk management program. On this note, Paquette et al. (2010, p. 252) state that it is desirable that such a program manages “policies intended to mitigate not only the common and easily identifiable tangible risks presented by cloud use, but those intangible risks that are specific to government operations and that affect all citizens. Without the appropriate level of oversight and governance, the tendency to implement cloud infrastructure and worry about the consequences later will lead to unpredictable and undesirable consequences to the nation’s information.”

8.3.7 Urban Development and ICT Project Management: Risks and Uncertainties and the Time–Cost–Quality Dilemma

In addition to international standards, cost, time, quality, performance, and risk are the key components through which trade-offs can be made and program status be tracked. Risk management applies proactive identification of future problems and understanding of their consequences, i.e., unwanted or unfortunate consequences subsequent to the possible effect of events on some form of assets, which allows for determining predictive decisions about urban development and ICT projects in the context of smart sustainable cities.

8.3.7.1 Urban Development Projects

Given their scale, complexity, and extension, smart sustainable cities as a set of interrelated urban development projects and programs do not often live up to the initial quality, time, performance, and cost specifications due to the inherent complexity of the risks associated with the delivery of large-scale projects. These issues tend to be common to the management of all kind of city projects, as these are inherently risky due to long planning horizons, entail changes in ambition (e.g., when new technologies and design principles associated with sustainability become available), and involve multi-stakeholder-oriented decision-making and planning processes with conflicting interests. Nevertheless, inaccurate planning of, and thus misinformation about, risks could still be mitigated or eliminated. In this regard, urban planners and developers should account for potential risks and uncertainties and related impacts early on, i.e., negative unplanned events and their consequences, by pursuing a thorough risk and uncertainty analysis due to the high-level risk and uncertainty associated with urban development projects. This key aspect of risk and uncertainty management is necessary because it allows for considering strategies that capitalize on the positive possibilities, conceding that solutions can be found which improve such projects.

Smart sustainable cities as a set of urban development projects constitute an enormous challenge that necessitates the ability to sustain the constant balance of time, cost, performance, and quality, thereby the inevitability of conducting a detailed analysis of possible contingencies, such as natural disasters, the rate of change, and the availability of resources. Uncertainty analysis should be conducted before the execution of plans takes place, as mentioned above. It is also advisable to perform uncertainty assessment many times during the project execution process due to the unpredictability surrounding design, construction, and ICT solutions deployment projects. Experiences with urban development projects show that uncertainty fluctuates, grows, and declines continually in response to the project environment, but is never eradicated completely. Moreover, it is difficult to achieve performance improvement on time, cost, and quality without detracting from one or two of them. Flyvbjerg (2007) provides a detailed discussion on the planning of urban development projects (specifically megaprojects) in terms of the involved risks, cost overruns, and benefit shortfalls and their causes which tend to be tangible and intangible. Problems in planning costs and benefit shortfalls as well as their causes are key issues to consider in the context of smart sustainable cities. Most urban development project empirics point to misinformation about costs, benefits, and risks due to a lack of accounting for contingencies, i.e., unaccounted for unplanned events. Statistical evidence demonstrates that the inherent risks pertaining to long complex interfaces, multi-stakeholder-oriented decision-making and planning processes, conflicting interests, and the temporal changing scope and ambition of the project with regard to design are often unaccounted for, thereby leaving room for contingencies to emerge—which leads to cost overruns and/or benefit shortfalls (Flyvbjerg 2007). Cost overruns are ascribed to stakeholders' misrepresentation and delusional optimism of the actual costs so as to ensure project approval (Flyvbjerg 2006). Urban stakeholders ought to possess enough information to know how to selectively disclose information to best serve their goals. Psychological factors are key justifications for inaccuracy in planning of costs and benefits. This involves planning fallacy and optimism bias: urban project planners may make decisions based on delusional optimism rather than on a rational weighting of gains, losses, and probabilities; they overestimate benefits and underestimate costs—in other words, they involuntarily spin scenarios of success and overlook the potential for mistakes or miscalculations, and the result is pursuing initiatives that are unlikely to come in on time (e.g., Flyvbjerg 2007).

As a set of urban development projects, smart sustainable cities necessitate an all-embracing sort of planning process to avoid potential failures in meeting the requirements with reference to any project goals defined at the initial phase, and hence to ensure successful outcomes. This has a lot to do with the lack of risk and uncertainty management, in addition to the other factors pertaining to the planning of complex projects, which may involve inaccuracies and ineffective use of sensemaking perspectives due to the unfamiliarity of urban planners to soundly interpret and strongly negotiate the narratives of urban projects. Hence, it is crucial to develop a detailed risk and uncertainty management plan, analyzing all contingencies and their potential implications for costs, time, quality, and performance in relevance to the development projects of smart sustainable cities. In this regard, from a general perspective, accounting for an optimistic estimate, a pessimistic estimate, and a most-likely estimate as an approach can be of much help to urban development project planners. Also checks of reality and thorough feasibility assessment of urban and technological design models and their integration are necessary so as to mitigate the effects of delusional optimism and planning fallacy as to overestimating benefits and underestimating costs. Lastly, for effective urban project management in circumstances of complexity, urban development project management should consider the planning of narratives by providing concrete interpretative frameworks, bringing about consensus between competing narratives within projects, and aligning effectively the activities of sense giving and sense taking (e.g., Alderman et al. 2005).

8.3.7.2 ICT Projects

In the domain of ICT, it is difficult to achieve the project objectives within the designated timeframe and to the agreed quality and cost due to the inherent complexity of the risks associated with ICT projects and their delivery. One of the challenging aspects of managing ICT projects is to include risks and uncertainties with task duration, effort, and cost. But a tendency to ignore the magnitude of the involved risks causes ICT projects to derail (Flyvbjerg et al. 2003) or fail. McManus and Wood-Harper (2008) conclude that risk management issues are not factored into projects early on, and are rarely discussed openly at project board, although they may be discussed at length behind closed doors. Therefore, ICT projects need to adopt a detailed risk analysis, which is an essential part of the planning function of ICT project management. Especially, ICT projects are associated with unpredictable behavioral patterns, unexpected changes, and common failures. There can always be a way forward to handle risks and uncertainty in ICT projects. Related management concedes that solutions can be found that improve ICT projects and the chance of their successfulness. It is thus essential to conduct risk and uncertainty assessment in connection to both the strategy work of the ICT project and the execution of the related plans. Being of particular relevance to ICT projects, the former should be, according to Erling (2008), conducted before the project plans are drafted; it allows for considering strategies that capitalize on the positive possibilities, while the latter can be conducted before the execution of the plans takes place. Risk and uncertainty management aims, given its defensive nature, to shield a project (plan execution) from potential outside threats. Given the unpredictability surrounding ICT projects, it is advisable to perform uncertainty assessment many times during the execution process. As with urban development projects, uncertainty fluctuates, grows, and declines continually in response to the environment, but is never eradicated completely. Thus, it is imperative to adopt a management strategy to deal with uncertainty. A sound strategy to deal with uncertainty would be to partner with an outsourcer that can be more suitable as to providing the most effective ways of mitigating it. That is, farming out (outsourcing) this task of project planning to an external party, e.g., a firm specialized in handling ICT project uncertainty. This entails contracting out the activity in question to a more competent party to handle it and the related harmful outcomes. This strategy gives the project an opportunity to get rid of tasks associated with high risks (Erling 2008). In general terms, outsourcing entails two organizations entering into a contractual agreement—legally binding contract, involving exchange of payment in which case the contracted agent accepts the risk for which it receives remuneration from the party managing the ICT project. The underlying assumption is that, as Erling (2008) argues, although we cannot eradicate the possible negative outcomes, we increase the chance of handling their economic fallout. Economic fallout is indeed what ICT projects suffer from due to their failures (e.g., McManus and Wood-Harper 2008).

As mentioned earlier, projects constitute a challenge that necessitates the ability to sustain the constant balance of cost, time, and quality. Rather, the so-called Iron Triangle (cost, time, and quality) are necessary criteria against which to measure the project management process (Turner 1993; Morris 1987). However, project managers are often faced with the cost–time–quality dilemma, and to deal with it, they tend to espouse different approaches depending on the nature, scale, and complexity of the ICT project. Regardless, it is difficult to achieve performance improvement on cost, time, and quality at once. Software development expects no thunderbolt solution to its various issues of cost, time, and quality (Brooks 1986). ICT projects usually use estimation method to tackle issues related to budget, schedule, and resource requirements. In the project estimates, it is necessary to take into account an optimistic estimate, a pessimistic estimate, and a most-likely estimate, an approach that is referred to as stochastic or statistical estimating (Taylor 2009). ICT projects tend to have time and cost as the prime objectives. A project must hit the on-time objective, or problems will follow (Atkinson 1999). Schedule duration and work estimation for each leaf activity in the work breakdown structure can be performed using a combination of different methods and data sources, including resource input, organizational project history data, and contractor project history data. The highest level activity in the WBS (after attaching schedule, resource, and cost estimates) reflects the schedule and cost estimates for the entire project based on the calculation done in terms of cost estimation for each activity according to the amount of work expected, the percentage of participation that each resource expects to make toward the activity. When estimating the project total cost, or effort, it is necessary to consider all project activities (Taylor 2009). Also, in ICT projects, re-estimation methods are used when necessary and performed using resource and contractor input. In this case, if schedule is adversely affected, organizational project history data is employed to determine whether or not to add additional resources to assist in completing the activity. Necessary updates to the cost, schedule, and resource estimates are usually included in the monthly software project management plan updates, but such re-baselining only takes place in extreme circumstances. These monthly updates are aimed to force allocated time toward maintaining such plan. Impromptu updates to the estimation plan are communicated to those affected; in particular, detailed explanation is given to the handling of communication of resource, cost, and schedule as update types.

While time and cost are calculated at a time when least is known about the project, “quality often changes over the development life-cycle of a project.” (Atkinson 1999, p. 337) It is critical to ensure the quality of the project deliverables in terms of the degree to which deliverables accord with the expectations of the base or client organization. In ICT projects, the external software quality assurance plan is used to assure that the quality of delivered work products is consistent with what is expected for the project by assisting in project processes, requirements completion and clarity, and quality assurance approach as risk factors. The quality assurance of the project deliverables is gauged against the similarity between deliverables’ specifications and what is actually delivered (Erling 2008). In ICT projects, quality reviews ensure that documentation products adhere to the standards upon which they are based, and that nondocumentation products to the designs/plans laid out by their input prerequisites. Informal functional audits of in-scope work products are held during the software testing and integration phases, and findings are documented. Commonly, audits are performed at the request of the project manager to verify adherence to the procedures described in the project plans.

Furthermore, uncertainty factors and related impacts tend to be not of prime focus in the prevailing ICT project strategy, despite the high-level risk associated with ICT projects. This is evinced by the failure of many ICT projects to deliver on time and to requisite specifications and budget. McManus and Wood-Harper (2008) found that a small number of projects are delivered to the original time, cost, and quality requirements due to the inherent complexity of the risks pertaining to the delivery of ICT projects.

8.4 Advanced Governance Models for Smart Sustainable City Development

8.4.1 Sustainability by Design or Governance and Urban Actors as Categories of Discourse

There are various categories of discourse about smart sustainable urban development to look at when pursuing questions pertaining to the planning and development of smart sustainable cities of the future. In this context, the discursive categories are aimed at providing insights into understanding the ways in which urban issues are socially constructed in terms of the combination of sustainability goals and smart targets, i.e., the grounds of the claims that smart sustainable cities can make cities intelligently more sustainable. Based on an extensive interdisciplinary literature review on smart and sustainable cities (Bibri and Krogstie 2017) and by extrapolating from earlier research within sustainable (and) smart cities (Bibri and Krogstie 2016), it appears that both particular aspects of the planning and development of smart sustainable cities and the way these are governed (e.g., citizen science and civic participation and engagement) are part of the underlying claims. On this note, at this stage of the planning and development of smart sustainable cities, among the urban practice challenges involved include strategies for strengthening both the capabilities of city governments regarding ICT solutions as well as governance and planning models (Höjer and Wangel 2015). In particular, the organization of smart sustainable cities entails a reconsideration of which kinds of actors should be involved in city governance and planning (e.g., Anthopolous and Vakali 2012; ITU 2014; Kramers et al. 2014). At the core of this is how citizens are engaged in, and actively shape, decision-making processes. Batty et al. (2012) point out that the urban sustainability issues will be dealt with using more effective models and simulations which entail an active engagement of a wider group of citizens in novel ways in the planning of their cities; in the information age, the city will be a determining factor for shaping policy analysis and planning, and the new technology will be a salient factor for planning forms of social organization. However, the issues around the development, planning, and governance of smart sustainable cities are subject to much debate among urban planners and designers as well as academics and policymakers. In the context of smart sustainable cities, to extrapolate from existing research on sustainable cities and smart cities (Bibri and Krogstie 2017), there will be both convergences and divergences around the way in which these issues can be addressed. Yet, a convergence on a particular way of addressing the issues of the development, planning, and governance of smart sustainable cities would allow to identify what it means to be, or should be, a smart sustainable city. These issues can be pursued by looking at the categories of discourse about smart sustainable urban development. Here, we focus on two categories: (1) urban sustainability by design and planning or governance and management and (2) urban actors. For the other categories of discourse in question, the interested reader can be directed to Bibri and Krogstie (2016).

The focus is on the contribution of design versus governance to achieving sustainability in smart sustainable cities. In terms of design and planning, such cities may view sustainability as an outcome of endeavors undertaken during the design and planning phase and the extent to which advanced ICT is emphasized as to its merger with sustainable urban forms: a city is a smart sustainable city because it has been designed and planned as such. As to governance and management, becoming a smart sustainable city may be contingent upon the way it can be governed and managed during and after the completion of smart sustainable urban projects: a city is a smart sustainable city because it is in its development and operation governed and managed as such. Kramers et al. (2016) provide some insights into how smart sustainable cities can be governed as such and how ICT and sustainability can be merged in the planning phase of their developments.

As regards to the actors driving smart sustainable cities, the idea pertains to those that should be involved in the development of such cities, which is crucial for understanding their vision with regard to sustainability. Cities as social fabrics and backbones of civilization are the result of dynamic, intertwined, multifaceted collaborations and networks of relations between and among people, communities, organizations, institutions, universities, and governments as urban constituents, with the aim of generating, disseminating, and implementing smart ideas and innovative solutions. As complex systems par excellence in light of the scientific and technological areas involved in their planning, smart sustainable cities entail a deep understanding of, and much of collective learning about, urban problems and systems. Therefore, they are developed through collaborative decisions and guided by a multitude of actions involving various players, i.e., multiscale, polycentric, and participatory governance-based planning and development processes. These have become even more complex through the very sophisticated technologies being used to understand, monitor, probe, and plan the systems of smart sustainable cities (see e.g., Bibri and Krogstie 2016, 2017). Of relevance to point out here is that the focus on governance has an empirical background in the widespread recognition of the complex, fragmented, and dynamic nature of cities as social systems (see e.g., Jessop 2002; Klijn and Koppenjan 2004; Kooiman 1993). In all, numerous kinds of actors are involved in the development of smart sustainable cities as large-scale urban projects and comprehensive plans, including government, public sector, private sector, citizens, communities, civil society, academia, and expert advisors. And each actor has a role to play, which may depend on, or be completed by another actor, as to shaping, developing, planning, organizing, and operating the smart sustainable city projects and initiatives.

8.4.2 The Role of Network Governance in Smart Sustainable City Development

Smart sustainable cities provide an opportunity that brings numerous stakeholders together and pool their substantive knowledge to put forth long-term plans that promote sustainable development. Maintaining the process of sustainable urban development toward achieving the goals of urban sustainability is a daunting challenge in terms of planning and requires a collective approach into coordinating actions and decision-making, thereby the necessity of governance and thus the significance of governance networks. Governance provides a means of understanding the relational dynamics between urban development and urban stakeholders in the long term—in other words, the way governance networks work, through different forms of network governance, toward sustaining the process of urban development toward sustainability. Network governance plays a key role in the attainment of successful network-level outcomes—network effectiveness (Provan and Kenis 2007), such as environmental justice, regional economic development, and community building. Specifically, network coordination in public sector provides considerable benefits, including enhanced learning, efficient use of resources, increased capacity to plan for and address complex problems, and better services for citizens (Provan and Kenis 2007). Furthermore, regulating governance networks through meta-governance has been of prime focus in governance research (Torfing 2005). Accordingly, shared network governance, a form which is governed by the network members themselves with no separate and unique governance entity (Provan and Kenis 2007), is seen to be the most effective for achieving positive outcomes in terms of sustainability as long as trust is widely shared among network participants (high-density, decentralized trust); network participants are relatively few; network-level goal consensus is high; and the need for network-level competencies is low.

8.4.3 Polycentric Governance Systems and Governance Networks

Polycentric systems are necessary to cope effectively with the complex problems of smart sustainable cities, and to give all urban stakeholders a more effective role in their democratic governance. In this context, polycentrism is the principle that guides the organization of cities around several political, social, environmental, and economic centers. The pluralization of political, social, environmental, and economic stakeholders and processes has stimulated the use of the "network" metaphor (Torfing 2005). Governance networks function through various forms of network governance (whereby network is viewed as a mechanism of coordination) to promote sustainable urban development. The power and efficiency gains of governance networks derive from their distinctive features. According to Bibri (2015), governance networks are characterized by the following:

- Horizontal articulations of public, semipublic, and private actors that are dependent on each other's resources and capacities but operationally autonomous;
- These actors carry out negotiations within an institutionalized framework based on an amalgam of normative, cognitive, regulative, and imaginary elements; and
- This framework is restricted by external forces as to its self-regulating patterns and actions.

The purpose of this framework is to contribute to the production of public purpose as an expression of plans, policies, and regulatory frameworks that are valid for, and directed toward, the general public.

The forms of coordination enabled by networks underlying polycentric governance systems can thus be an apt response to the question of how to tackle complex policy problems and governance tasks associated with the planning and development of smart sustainable cities (see Bibri 2015). This also explains and justifies why governance networks need to be formed and why they can contribute to efficient governance within the field of policy and planning in the context of smart sustainable cities as an instance of sustainability transitions. The network governance actors possess specific knowledge that is pertinent for decision-making, and when this knowledge is pooled together, it represents a crucial basis for making an astute choice of feasible options (Kooiman 1993; Scharpf 1999). Through developing their own logic of appropriateness, these actors regulate the process of negotiation, the formation of consensus, and the resolution of conflicts (March and Olsen 1995; Mayntz 1991). Network coordination provides considerable benefits, including enhanced learning, more efficient use of resources, increased capacity to plan for and address complex problems, and greater competitiveness (Brass et al. 2004; Huxham and Vangen 2005). This is of high relevance to the planning and development of smart sustainable cities. However, governance networks are likely to fail on various counts due to otherwise inefficient coordination. Careful network governance is essential for it might prevent major dislocations and mitigate the impact of various disturbances; yet, optimizing the functioning of governance networks on all dimensions is a daunting task (Kickert et al. 1997; Klijn and Koppenjan 2004) and poses special conundrums. In all, polycentric governance, coupled with favorable institutional frameworks, reduces the uncertainties for smart sustainable cities as sustainability transitions.

8.4.4 Social Norms and Regulatory Frameworks for Inducing Behavioral Change

Furthermore, integration approach, one of the theoretical approaches to governance developed by Torfing (2005), describes governance networks as institutionalized (established) field of interaction between relevant social actors that are integrated in a community defined by common social norms. Carlson (2001) sees social norms as a tool to increase sustainable practices among citizens, but also emphasizes the importance for governments to not rely only on social norms to achieve collective behavioral changes. This implies that while social norms can be an effective means to achieve collective outcomes, they still need to be supported by other regulatory measures to achieve public good. Studies demonstrating the power of social norms in resolving collective problems—"common bads"—among communities as members of small, homogenous groups have led to over optimism as to social norms providing solutions alone; it is to recognize that, when developing approaches to resolution of large-scale number, small payoff problems, the characteristics of the behavioral change should matter deeply in selecting the appropriate mix of policy or regulatory instruments to facilitate behavioral change and persuade people by understanding the role of social norms as to inducing desired behavioral change (Carlson 2001). In relation to this, Ostrom (2000) argues that intrinsic motivation should be supported by institutions that enable those motivated to solve problems as well as protect them from free riders.

8.4.5 Community-Led Management and Collective Management of Common Urban Resources

In relation to community, there is a general understanding that achieving sustainable urban development is dependent on the role the concerned communities play in decision-making processes as a collective endeavor. Community-led collaborations are often sought after in sustainable urban development practices, such as managing natural resource provisioning (Bakker 2008) or managing ecosystem services (Bonnell and Koontz 2007). However, there is a tendency to romanticize the accountability and democracy associated with community-led management, "thereby denying the progressive potential of state-led redistributive strategies" (Bakker 2008). Besides, there are other factors that are likely to influence the successful attainment of public good and its provision, which can be provided by government such as tangible resources necessary to achieve the desired common outcomes. However, according to (Ostrom 2000), achieving common goals is associated with the *free-rider* issue, citizens not contributing to the public good may still enjoy the benefits achieved by community collaborations and social norms. This is referred to as the "zero contribution thesis"; if everybody in a city would live in accordance to this thesis, that city would definitely fail so would sustainable development. One of the main foundations of sustainable development is the contribution and participation of every citizen in the community in the process of planning and in achieving public goods and benefits. Indeed, multilevel systems are needed to cope effectively with the complex problems of modern life and to give all citizens a more effective role in the governance of democratic cities.

In terms of collective management of common urban resources, Foster (2011) highlights that collectively shared urban resources—“urban commons”—suffer from regulatory slippage, i.e., the government inability or unwillingness to effectively manage and control those common spaces, which results in open access to rivalrous urban resources and unequal, incompatible or even competing uses. In fact, to restore the resources to a state of equilibrium between users and uses, a new governance regime is required. Instead of traditional approaches like government regulation and privatization, collective management of common urban resources is the preferred alternative, in which a group of users is able to overcome collective action problems to manage a common urban resource without government coercion or private property rights. From a sustainability perspective, collective management preserves social viability of neighborhoods and city life, as well as produces efficiency or even innovation in the provision, oversight, and use of those resources. Therefore, central and local government authorities support these collectives by reducing transaction costs of cooperation and help the actors to leverage their efforts to achieve high economic and social payoffs from their collective action. Government support can also help stabilize groups and sustain the collectivity over time. In fact, the level of enabling offered by local government inversely relates to endogenous factors such as community size or shared norms. On the one hand, smaller, more homogenous user groups need a less strong government role. On the other hand, larger scale, complex resources where resource users are more heterogeneous and lack a high level of social cohesion require an increasing or stronger government authority, i.e., if the presence of endogenous factors decrease, the government role can increase and vice versa. In all, as argued by O’tootle and Meier (2004), straightforward political action in government bodies should serve as administrative bodies assisting the collaboration of many stakeholders in decision-making processes, but they warn that the addition of stakeholders complicates effective outcomes or achieving goals. In this regard, Provan and Kenis (2007) suggest two forms of network governance: lead organization and network administrative organization: as appropriate forms to adopt when the number of stakeholders is moderate and goal consensus is moderately low and when the number of stakeholder is moderate to many and goal consensus is moderately high, respectively. Indeed, it is crucial to adopt a suitable form of network governance as a mechanism of coordination based on the nature and scale of sustainable urban development endeavors and programs, in particular in relation to their continuous evolvement—e.g., the stages subsequent to the development of smart sustainable cities.

8.4.6 City Governance Structures: New Forms of Governance and Widespread Participation of the Citizenry

One of the goals of smart sustainable cities is to develop new forms of urban governance, and one of the scientific challenges thereof is to develop technologies that ensure shared knowledge for democratic governance and informed, widespread participation. The goal of new forms of governance can be achieved by devising new ways of reengineering smart sustainable cities of the future to make them equitable, responsive, resilient, prosperous, environmentally friendly, and safe by means of advanced ICT. As to the challenge in question, ICT of the next wave of computing underlying smart sustainable cities of the future is fundamentally network-based and ubiquitous and enables extensive interactions across many spatial scales and urban domains. Using state-of-the-art data systems and distributed computing across smart sustainable cities as part of the coordination and integration processes will allow citizens by means of advanced tools to participate and to blend their knowledge with that of urban experts from different city-related disciplines and fields who are developing and applying technologies supportive of widespread participation.

What is required for governance in the context of smart sustainable cities of the future are new frameworks that take account of the new sources of, and extensive access to, data that citizenship is making possible. This relates to issues of widespread participation of the citizenry in relation to several functions of city governance. Research endeavors in this regard should pull together much of the modeling capabilities built on the integrated data systems envisaged with the development of smart sustainable cities. One of the key foci in this research is to develop advanced database types and powerful modeling functions in an ICT framework to build up e-governance tools and connect the cooperative participation with the personal knowledge of citizens with respect to promoting environmentally friendly activities, e.g., low-energy/low-carbon mobility, effective accessibility, sustainable and efficient transport, demand-based utility, and context-aware health care. Research efforts in this area should take into account security issues related to data access online, privacy, confidentiality, intelligent interfaces, standards for data and model development, and so on. City institutions must embody—in response to the changes pertaining to smart sustainable cities in terms of models of their functioning due to ICT of the new wave of computing—a degree of flexibility unlike that which is adopted by current city organizations tasked to deal with the future issues related to cities. In this regard, "issues of responsibility, openness, transparency, access to public data and the regulations that extra national government agencies may impose on what and how and where and why citizens are able to influence the governance of their cities" (Batty et al. 2012) will be central but so will ICT of the new wave of computing.

To realize the above requires a major shift in the development of ICT infrastructure that underpins smart sustainable cities through distributed computing and ubiquitous networks available to, and also accessed by, all citizens using devices enabling access to such infrastructure. Here, the questions of governance and security become crucial to their ability to access such infrastructure. This also requires coordination based on advanced digital network governance so that services can be delivered most efficiently and effectively. Such service delivery will enable the data that will be routinely collected and automatically generated to make cities smart sustainable over different spatial and temporal scales. Only then can such data open entirely new windows of opportunity for solving sustainability issues that we have never had before. The whole idea is that we need to merge emerging digital technologies with existing nonautomated, non-digital technologies, and thus enable them to co-exist in an integrated fashion. In all, the major intellectual challenge facing smart sustainable cities and that we need to resolve in developing truly such cities that will benefit the health of the city and quality of life of all its citizens is to embrace the idea that the development of digital technologies are those which can be used to investigate the processes of their own application, implementation, and influence on the city (Bibri and Krogstie 2017). In this respect, "it is likely that participation in formulating policies might be very different from the past when futures were dictated by the elite, primarily because of its access to information. Already it is clear that a citizenry which is informed through the power of the net is beginning to make a difference as new forms of data and advice are being implemented using crowd-sourcing. New forms of preference elicitation are being generated using mobile and other applications…. These are profound changes that we need to mobilize using the equally powerful science that future ICT will unleash." (Batty et al. 2012, p. 485).

There is space for further discussion to argue the point that ICT of the new wave of computing has disruptive, substantive, and synergetic effects, particularly on forms of urban management and organization that are required for future forms and models of governance for smart sustainable cities.

8.4.7 Big Data Governance

8.4.7.1 Mayoral Institutions for Digital Governance for Situating the Application of Big Data Innovations

The emergence of urban big data is opening unique opportunities to develop and advance big data practices in terms of more innovative urban indicators and targets of relevance to sustainable development, and thus to leverage big data innovations and leapfrog complex challenges pertaining to diverse urban issues associated with broader sustainability goals. This can be accomplished by various means and endeavors. One of which is to develop mayoral institutions for the governance of urban big data for situating the application of related innovations (Kharrazi et al. 2016) in the context of smart sustainable cities. Here, the impetus is to use the routinely collected and daily generated data across urban domains to potentially make urban services more transparent and efficient, foster innovations through new data-driven decision-making processes in organizations, and alter decision-making structures and systems, while taking into account the numerous challenges associated with big data management and analysis and finding ways to overcome them (see Chap. 9 for a detailed account of these challenges and how to tackle them). To circumvent these challenges from a governance perspective, urban policymakers should develop central mayoral institutions which process, analyze, manage, govern, coalesce, expand, and financially support critical urban datasets. In particular, addressing the privacy and ethical dimensions should be in the forefront of the minds of urban policymakers as part of a long-term vision for the governance of urban big data, without stemming the momentum of related innovative applications. Further, mayoral institutions play also a key role in formulating strategies and practices to support open data that facilitate knowledge sharing and allow more focused sustainable development. There is growing and strong evidence that open data in the context of smart sustainable cities can help city governments in promoting informed participation, transparency, information equality, and shared knowledge among citizens, in addition to facilitating the endeavor to collectively reflect and find solutions to the environmental, social, and economic challenges of sustainability and urbanization (Batty et al. 2012; Kharrazi et al. 2016). Besides, smart sustainable cities should promote government initiatives and endeavors to ensure access to government data, as well as to increase participation and leverage innovation through public co-creation and open innovation. Indeed, “a number of national governments have developed initiatives in opening up public data to a wide audience of interested publics and professionals. So far, following the lead of the US, many other countries such as the UK and many city governments have taken up the challenge and are making public data available in many different formats. This is also part of the transparency agenda in contemporary government, which is founded on accountability but it also relates to questions of confidentiality and privacy. The EU is also heavily involved in these issues” (Batty et al. 2012, p. 500). In fact, to increase their contribution to sustainability, smart sustainable cities should put in place knowledge sharing platforms to promote and advance sustainable practices through big data applications pertaining not only to planning but also transport, energy, water, waste, mobility, environment, governance, social cohesion, quality of life, equity, and participation. Citizens should be fully aware of the kind of public knowledge infrastructure they have access to and can contribute to and the potential benefits they will be able to get from it in the context of sustainability. They should also be in full control of how and their data are being collected, managed, and analyzed and for what purpose they are used, when, and for how long. Again, “only a public system capable of delivering high-quality information within a trusted framework has the potential for raising a high degree of participation, and only large, democratic participation can ensure the creation of reliable, timely and trustworthy information about collective phenomena. This view is at the basis of a citizens science, where sentiment and opinion mining from trusted information can detect shifts in collective mood in a timely manner, detect the weak signal of important changes, and detect the structure and evolution of social communities." (Batty et al. 2012, p. 492).

Public participation has become at the heart of institutionalized urban development with the recent digital transition in ICT with regard to big data analytics technologies. The ability for all citizens to communicate with each other and with a wide number and variety of agencies, institutions, and groups that they deal with has provided a new sense of urgency and crystallized the notion that smart sustainable cities are based on communities whose citizens can play an active part in their operation, development, and planning in the context of sustainability. This requires that citizens have access to information about what is happening in their cities, as well as devising methods for enabling a wide range of different groups to become actively involved in the related planning and development processes using data, models, and scenarios informed by big data technologies and platforms. New digital media, social media, and the web are all improving the liquidity of this type of interaction and thus participation as both data and plans are being shared (Brail 2008). Participation is becoming more in the spirit of the way complex systems evolve from bottom-up (Batty et al. 2012). As part of the vision of smart sustainable cities, an informed citizenry will be able to engage with experts, administrators, and planners from diverse areas of urban sustainability in generating scenarios for improving the contribution of such cities to the goals of sustainable development in ways that hitherto have not been possible with respect to the quality of urban life and the efficiency of urban performance in line with such goals. This is expected to demand a citywide mobilization of resources, capabilities, and actors, which imply advances in big data, models, and policy integration. One of the scientific challenges for smart sustainable cities of the future is to develop and successfully implement participatory technologies on a citywide scale basis.

8.4.7.2 City Government Role

Governance of big data is a critical step toward mainstreaming the uses and benefits of big data in the context of smart sustainable cities. It is about devising relevant strategies for ensuring that vital data assets across urban domains and entities are governed, regulated, and managed. This process ensures that urban data can be trusted, shared, and made liable, especially when directed for sustainability purposes. Therefore, it is crucial to develop regulatory frameworks for utilizing big data in relation to sustainability, as well as to specify who should implement these frameworks as to the city stakeholders involved in the design, development, and deployment of big data applications as part of smart sustainable urban development. Governance of big data entails applying available technological capabilities to help create smooth practices and operations within smart sustainable cities. To keep the flow and exchange of big data under control requires establishing guiding principles by the urban governing entities to ensure participation, collaboration, and transparency, to draw on Bertot and Choi (2013). Besides, it is upon the fact that big data offer unique opportunities to use the statistics of the urban operations, functions, and citizens in conjunction with the real-time data that the data governance techniques should be employed by mayoral institutions to ensure the safe use of big data. This aids in establishing that all the information that exist within urban entities is governed.

The role of city governments is essential to sustaining the contribution of the urban stakeholders involved in promoting smart sustainable urban development by ensuring adequate systems to govern and utilize big data generated by different urban entities. Indeed, in the context of smart sustainable cities, planners, strategists, decision-makers, and leaders operate within networks of stakeholders that uncover and identify their common goals as to the implementation of big data applications as well as the needed course of action to achieve them. Here, regulatory frameworks as linked to varied groups of stakeholders need to provide an environment conducive to the process of articulating and negotiating common goals, interests, and strategies. In addition, city governments must continuously reevaluate data policies as necessary in terms of quality, privacy, storage, reuse, accuracy, access, and conservation, which entail ensuring informed use of large datasets through codebooks and well-defined data documentation (Bertot and Choi 2013). Furthermore, it is important for city governments to define the role of citizens' control in order to effectively support big data applications related to city services, thereby balancing the beneficial uses of data against individuals' privacy concerns (see Tene and Polonetsky 2012).

8.4.8 Research Opportunities for the Governance of City Development

There are several research opportunities and horizons that are worth exploring in the field of governance for the development of smart sustainable cities of the future with respect to the models of their functioning. They include, but are not limited to, the following:

Enhancing the distinct structural properties of the predominant forms of network governance in planning and development processes of smart sustainable cities in response to their specific requirements and objectives with regard to the dimensions of sustainability and their integration;

Identifying the salient contingency conditions that are likely to affect the successful adoption of a particular form of network governance, and how they in turn affect network effectiveness in terms of the coordination mechanisms in the context of smart sustainable cities. One of the key foci of research in this regard is to endeavor to streamline network governance in terms of attaining positive outcomes in terms of sustainability;

Understanding the functioning of governance networks, the process by which certain network conditions lead to various network-level outcomes. This is crucial for it provides insights into grasping why and how such networks produce certain outcomes, irrespective of whether they are the product of strategic decisions made by network participants or result from bottom-up processes (Provan and Kenis 2007);

Identifying the conflicts and tensions inherent in the governance-based processes of the development of smart sustainable cities and devising new ways of how they can be civilized and managed, with the purpose to increase their contribution to the goals of sustainable development;

Investigating further the role of governance networks in facilitating joint action coordination and collective decision-making across local, regional, national, and transnational levels in order to be able to extend and mainstream the development of smart sustainable cities within a given nation;

Exploring the extent to which the dominant social and environmental discourses shape and guide the negotiated interaction in governance-based processes of planning and development of smart sustainable cities;

Although several studies have been carried out over the last decade investigating governance networks, very little is known about the functioning of such networks with regard to the different spheres of the development of smart sustainable cities;

There is still a considerable discrepancy between the knowledge about the overall functioning of networks and the acclamation and attention networks receive (Proven and Kenis 2007). This is of high relevance to smart sustainable cities;

No studies have focused directly on governance-based processes of planning and development of smart sustainable cities as new urban models, especially the issue of governance network functioning is one of the recent preoccupations of the research agenda of governance network research;

As in the coming years, governance networks pertaining to the development of smart sustainable city endeavors will face enormous challenges as to action joint coordination and collective decision-making for advancing sustainability, it is crucial to enhance network governance frameworks so to streamline network functioning in terms of effectiveness and management of conflicts and tensions in the planning and development processes, with an emphasis on the goal of protecting the environmentally sustainable, promoting the economically growing, and advocating the socially equitable city;

The study of effectiveness has been problematic at a network level, and although governance networks have been studied from a variety of perspectives, a little attention has been given to network governance from a general perspective (Provan and Milward 1995), as well as to the governance of networks in relation to the development of smart sustainable cities. The underlying assumption is that specific forms of governance are most likely to produce positive results for smart sustainable cities This focus is what Powell et al. (2005) refers to as “illuminating the structure of collective action”;

Developing a deep understanding of network governance in the development of smart sustainable cities requires collection of data on operative networks, which can be time consuming and costly;

There is a need for a much stronger intelligence function for coordinating the many different components that comprise smart sustainable cities, which will depend on some sort of structure that brings together the functions of city government and the activities of semipublic and private organizations involved in service delivery. This intelligence function is based on the idea of integrating the expertise provided by such organizations in the area of hardware, software, and data solutions enabling cities to be smart sustainable with the government role in engaging citizens as users of urban services as well as their interests in terms of the quality of life and well-being of their communities;

Developing and coupling databases as part of new governance structures for the new intelligence functions of smart sustainable cities that utilize much wider participation in decision-making based on real-time construction and use of a variety of simulation models and optimization methods;

Advanced forms of decentralization of governance in the sense of creating several agencies responsible for different kinds of urban services, especially smart sustainable cities are seen as constellations of active agencies and groups, thereby the relevance of governance and coordination being based on both the bottom-up as well as the top-down approach and extending to the many functions envisaged and to be coordinated in such cities;

In relation to new organizational infrastructures for smart sustainable cities built around new developments in ICT, it is important to further investigate the issues of privacy, security, social inclusivity, and user empowerment, as well as a host of issues that are being changed by ICT of the new wave of computing;

More focus should be given to new research area of governance related to the operation of utilities, the access of citizens to services (health care, social support, transport, education, etc.) and facilities, and any functions having a spatial effect on smart sustainable cities in terms of mobility and location; and

Developing online and mobile forms of participation using extensive ICT, whereby the citizenry can be massively engaged in working toward improving relevant aspects of smart sustainable cities alongside sustainability strategists and leaders and urban planners and designers from government, academia, and industry. Central to these new forms of participation are the decentralized notions of governance and community action.

8.5 Conclusions

Smart sustainable cities are complex systems par excellence, more than the sum of their parts. They are inherently intricate through the very technologies being used to monitor, understand, and analyze them in relation to their management, planning, and development to improve their contribution to sustainability and their ability to confront urbanization. Accordingly, they deal with complex challenges and significant risks as dynamically changing urban environments. As such, they require advanced and innovative approaches into the management of their complexity. The principle aim of this chapter was to explore urban and ICT project and related risk management in the context of smart sustainable cities, as well as the various models of governance of their functioning and development. The emphasis in risk management was placed on both urban development and ICT projects as well as information security in relation to the use of cloud computing as an increasingly widely applied solution for big data and context-aware applications. Regarding governance models, the emphasis was on polycentric, participatory, and big data forms of governance.

We have addressed a wide variety of aspects and issues of urban development and ICT project management, covering conceptual, analytical, critical, and practical perspectives, while emphasizing the complexity of smart sustainable cities and providing some potential ways to deal with it. We have focused on the main project management functions, namely planning, organization, and controlling and monitoring. These have been adequately discussed in relation to urban development and ICT projects given the generalizability of the project management framework being in use, with some minor differences associated mostly with technical details, in addition to the scale, complexity, and extension of both kinds of projects. Smart sustainable cities involve a massive use of ICT to advance their contribution to the goals of sustainable development. This entails that ICT projects pertaining to big data analytics and context-aware computing as a set of novel applications span over different urban domains, including transport, energy, building, mobility, environment, health care, education, safety, governance, and so on in terms of operations, functions, services, designs, strategies, and policies. Such projects as typically associated with software development are intended to design, develop, and implement big data and context-aware applications as part of the ICT infrastructure of smart sustainable cities. Similarly, urban development projects involve transport systems engineering, energy systems engineering, building construction, physical and spatial structures development, mobility systems development, distribution network systems development, communication systems development, water and waste systems engineering, traffic systems engineering, healthcare and education facilities development, neighborhoods and intercity (re)development, and new-built and state-led gentrification. Furthermore, there are several challenges pertaining to ICT and urban development project management that need to be overcome to enable smart sustainable cities to realize their full potential in terms of advancing sustainability.

Moreover, we have introduced different risk functions, namely management, assessment, and analysis, and clarified the related conceptual ambiguities and differences. In addition to providing a detailed account and discussion of risk dimensions and issues, we have identified the significant risks associated with information security and urban development and ICT project management that need to be mitigated to enable the development of smart sustainable cities. While the move to cloud computing has become a land rush, increasing in importance as part of the ICT strategy of city governments in several ecologically and technologically advanced nations, there are many risks that should be taken into account when considering the adoption of cloud computing solutions. Information security is one of these risks to think carefully about before making decisions related to the ICT infrastructure of smart sustainable cities. Nonetheless, due to the increasing adoption of cloud computing solutions in recent years, justified by the fact that their advantages outweigh their disadvantages, research communities provide hopes for constructive alternatives by using new approaches into addressing the related conundrums. There have moreover been efforts from the industry community to address cloud computing issues in terms of automating the assertion, assessment, audit, and assurance of cloud computing environments, as well as in terms of developing best practices and providing forums to discuss common problems and solutions (e.g., Kalyvas et al. 2013a, b). As to urban development projects, smart sustainable cities are required to consider risk management and uncertainty analysis to avoid potential failures in implementing programs and initiatives, and thus to ensure successful outcomes with regard to achieving the goals of sustainability. Existing risk management and uncertainty analysis approaches applied in project management are instrumental and useful as to identifying, measuring, monitoring, controlling, mitigating, and eliminating potential risks and uncertainties in relation to the development of smart sustainable cities as long horizon planning endeavors. However, risks related to urban development and ICT project management are difficult to deal with in both cases, especially when it comes to megaprojects and large-scale endeavors, respectively. Therefore, we have proposed different approaches into dealing with such risks and provided fertile insights into understanding the related time–cost–quality dilemma as ways to mitigate such risks. In particular, smart sustainable cities should have the skills and resources to think about ICT projects pertaining to big data analytics and context-aware computing, and be able to join up their thinking across departments and local authority boundaries.

Furthermore, we have introduced and discussed different concepts and models of governance in relation to smart sustainable cities. The main topics addressed included polycentric governance, network governance, governance networks, participatory governance, and big data governance. Together with these, we have identified relevant research avenues that are worth pursuing to enhance the management of the complexity of smart sustainable cities. Indeed, such cities require advanced and new forms of governance for the management of their development with respect to their contribution to the goals of sustainable development and to the use of emerging and future ICT to strategically assess and sustain this contribution. New circumstances require new responses. In particular, the use of emerging and future ICT to engage the citizenry at large occurs through constellations of instruments and planned initiatives and programs that build upon active, online involvement of wide groups of citizens in addressing and resolving the pressing issues and complex challenges of sustainability by means of innovative ICT-based techniques and methods, coupled with strong organizational structures. In this regard, it is more likely that the involvement of citizens in formulating urban policies associated with sustainability will take a different route in the future; as ICT savvy citizenry has already begun to make a difference. Civic participation and engagement will be in the context of smart sustainable cities basic ingredients for urban policymaking, management, and planning. It has become necessary to mobilize positive and profound changes—e.g., sustainability—using the power of ICT that the new wave of computing is unleashing and will further leverage as the time evolves. The underlying assumption is that ICT and computing as a form of science and technology will permeate urban systems and domains in an increasingly computerized and urbanized world.

In addition, of importance is to retain simultaneously a balance between the power of the dominant collective groups (institutions, organizations, and industries) and those of civil society (citizens and communities) given the positive force of the collective effort in achieving the long-term goals of sustainability. The question of power and with whom it resides is central here, and civic engagement entails reclaiming this power from the institutions, organizations, and industries. This is to create a fertile environment that advocates negotiation among and participation from all urbanites for the purpose of contributing together to the efforts for responding to the challenges of sustainable development with support of advanced ICT in an increasingly technologized and urbanized world. In particular, there exist always conflicts of interests at, and across, the macro- and micro-level of the city that should be addressed when it comes to environmental sustainability endeavors and initiatives. Overcoming these conflicts is necessary for the public to act. Assuming that it is culturally unthinkable to do without ICT since it undergirds the functioning, and will shape the evolution of, smart sustainable cities of the future, and hence there is no escape from it—a sound way to solve unshakable conflicts is through conflict resolution and thus a wide participation of the affected people rather than solely forcing new policy instruments and regulatory frameworks, as this seems to generate more power imbalances and further conflicts of interests between the constituents that have a stake in the organization and development of smart sustainable cities. In addition, there are also issues over the extent to which citizens have full access to appropriate technologies, especially among low-income groups and older people, leading to potential digital exclusion of urban kind.

Lastly, the role of city governments is essential to sustaining the contribution of the urban stakeholders involved in promoting smart sustainable urban development by ensuring adequate systems to govern and utilize big data generated by different urban entities. Besides, the political action is determining in terms of how smart sustainable cities as techno-urban innovation systems can be developed and will evolve and perform with respect to contributing to the goals of sustainable development. A drastic shift to techno-urban innovation systems is unlikely to proceed and function without parallel political action (Bibri and Krogstie 2016).

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Chapter 9

Big Data Analytics and Context-Aware Computing: Characteristics, Commonalities, Differences, Applications, and Challenges

Abstract Data sensing and information processing are being fast embedded into the very fabric of the contemporary city in terms of its environments, systems, and processes, while wireless networks are proliferating in ways that are hard to imagine. This has been fueled by the new digital transition in ICT—enabled by an integration of various forms of pervasive computing—and justified by its potential to enhance the city operations, functions, services, and designs. Driving this transition predominantly are big data analytics and context-aware computing and their increasing amalgamation within a number of urban domains, especially when their functionality involves the same core enabling technologies, namely sensing devices, computing infrastructures, data processing platforms, and wireless communication networks. However, topical studies tend to deal largely with this new wave of urban ICT in connection with economic growth and the quality of life in the realm of smart cities, and thus ignore its potential in improving sustainability in the realm of smart sustainable cities. This endeavor is a first attempt to address the combination of big data analytics and context-aware computing in the realm of smart sustainable cities with respect to their contribution to the goals of sustainable development. This is an unexplored research area that has brought new and significant challenges for the development of smart sustainable cities. This chapter explores and reviews the real potential of big data analytics and context-aware computing for improving sustainability in the context of smart sustainable cities. In doing so, it enumerates, describes, and discusses the state-of-the-art data-centric and context-aware applications pertaining to diverse urban systems and domains, as well as identifies the key challenges involved and sheds light on the open issues stemming from these challenges. We argue that combining big data analytics and context-aware computing could be leveraged in the advancement of urban sustainability, as their effects reinforce one another as to their efforts for transforming the processes operating and organizing urban life in this direction by employing and merging data-centric and context-aware applications to enhance, harness, and integrate urban systems as well as to facilitate collaboration and coupling among diverse urban domains. This study can serve as a benchmark for urban researchers, planners, and policymakers for the development of smart sustainable cities of the future in the context of big data analytics and context-aware computing.

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Context-aware computing · ICT of the new wave of computing
Urban sustainability · Big data and context-aware applications

9.1 Introduction

Smart sustainable cities typically rely on the fulfillment of the prevalent ICT visions of the new wave of computing, where everyday objects communicate with each other and collaborate across heterogeneous and distributed computing environments to provide information and services to diverse urban constituents (urbanites and entities). The most prevalent forms of pervasive computing are UbiComp, AmI, the IoT, and SenComp. Heralding a major technological change characterized by an ever-growing embeddedness of ICT into urban systems and domains, these socially disruptive technologies are projected to result in a drastic transformation of the techno-urban ecosystem in all its complexity and variety. This will, in turn, alter how ICT can be applied and used in all urban spheres with far-reaching implications. It has in fact been suggested that as ICT becomes pervasive, i.e., permeate urban infrastructures, architectural designs, ecosystem services, public and social services, administrative services, and citizens' objects, we can speak of cities getting smarter as to addressing environmental, social, and economic problems as well as providing services to citizens to improve the quality of their life (Batty et al. 2012; Bibri and Krogstie 2017a, b; Piro et al. 2014; Shepard 2011; Townsend 2013). Big data capability and context-aware behavior are considered as prerequisites for realizing the novel applications pertaining to UbiComp, AmI, the IoT, and SenComp (e.g., Batty et al. 2012; Bibri and Krogstie 2017a, b; Böhlen and Frei 2009; Coutaz et al. 2005; Schmidt 2011; Shepard 2011; Solanas et al. 2014; Vongsingthong and Smanchat 2014). Specifically, big data trends are associated with the IoT and UbiComp technologies and context awareness trends with AmI and SenComp technologies. In all, the expansion of these computing trends as to the underlying technologies and applications are increasingly stimulating smart sustainable city initiatives and projects in ecologically and technologically advanced nations (e.g., Bibri and Krogstie 2016a).

The notion of big data analytics and its application in urban analytics (see Chap. 4 for a detailed discussion with illustrative examples) have attracted enormous attention among urban scholars and practitioners over the past few years. The big data paradigm is fundamentally changing the way cities function and can be managed, driving decision-making in urban planning and development in the context of sustainability (see Chap. 5 for more details). The digital data are projected to grow from 2.7 to 35 Zettabytes by the year 2020 (Malik 2013). It is estimated that more data are being generated every day than, roughly, in all of the period prior to a decade or so back. Around cities, an exponentially growing amount of data continues to be produced beyond imagination, and the sheer volume of information that is already available out there coming from diverse urban domains is at such high value that it would be astute for urban planners and strategists in collaboration with ICT experts to exploit it for improving sustainability. Indeed, big data provide fascinating opportunities to change how things can be done in cities in terms of operation, management, and planning from a sustainability perspective, to reiterate. Unsurprisingly, big data analytics as a general area applied to various urban domains has become of prime focus in the research field of smart sustainable cities (Batty et al. 2012; Bibri and Krogstie 2017a, b). It is associated with a wide variety of applications pertaining to the environmental, economic, and social dimensions of sustainability. Hence, it is clearly on a penetrative path across the urban domains that rely on ICT, which involve natural resources utilization and management, infrastructures and facilities operation and management, and well-being and quality of life enhancement. Its main strength lies in the high influence it will have on many facets of smart sustainable cities and their citizens (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Pantelis and Aija 2013). Therefore, big data analytics is growing rapidly. The big data movement has been propelled by the intensive R&D activities in academic circles as well as in the industry, with huge expectations for further innovations and advancements.

Context-aware computing as a prerequisite enabling technology for ICT of the new wave of computing constitutes a key component of the ICT infrastructures of smart sustainable cities (e.g., Solanas et al. 2014; Kamberov 2015; Bibri and Krogstie 2017a, b) and future smart cities (e.g., Riva et al. 2005, 2008). A smart urban environment is a set of context-sensitive systems based on the pervasive computing, in which the city interacts with its citizens and components through embedded devices and sensors. Having access to context information in smart sustainable city applications and systems plays a key role in supporting decision-making processes pertaining to sustainability (e.g., Al Nuaimi et al. 2015; Bibri and Krogstie 2017a, b; Solanas et al. 2014). It is becoming increasingly evident that smart urban environments based on the context-aware technologies will be commonplace in cities in the near future to support sustainable urban living in various ways (see, e.g., Bibri and Krogstie 2016a, 2017a; Böhlen and Frei 2009; Shepard 2011; Thrift 2014). Local city governments are investing in advanced ICT to provide technological infrastructures supporting AmI and UbiComp, as well as to foster respect for the environmental and social responsibility (e.g., Solanas et al. 2014). Thus, there are many opportunities for smart sustainable cities to embrace and leverage from the use of context-aware technologies due to the role they play in several important areas, including energy, environment, education, health care, utility, and public safety (Bibri and Krogstie 2017a). In light of this, technologies for context-aware applications concerning design, development, and implementation are rapidly maturing in response to the emergence of smarter cities enabled by ubiquitous, sentient, ambient, and IoT computing, as well as to the underlying challenges associated with their incorporation of and contribution to the goals of sustainable development to evolve toward smart sustainable cities (Bibri and Krogstie 2016a, 2017a, b).

Despite the recent increase of research on big data analytics and context-aware computing in the urban domain, the bulk of work tends to deal largely with applications related to economic growth (banking, customer relationship management, targeted marketing, manufacturing and production, medicine, science, etc.), and the quality of life (employment, utility, housing, safety, etc.) in the realm of smart cities (e.g., Belanche et al. 2016; Bibri and Krogstie 2017a, b; DeRen et al. 2015; Kitchin 2014; Kumar and Prakash 2014; Solanas et al. 2014), leaving important questions involving how and in what ways big data analytics and context-aware computing can add to the environmental, economic, and social dimensions of sustainability in the realm of smart sustainable cities barely explored to date. Indeed, most of the definitions of smart cities fail to incorporate sustainability (e.g., Bibri and Krogstie 2017a), and economic and social aspects tend to prevail (e.g., Ahvenniemi et al. 2017). In particular, they say little about the environmental performance of cities (e.g., Bibri and Krogstie 2017a; Höjer and Wangel 2015; Kramers et al. 2014). In addition, a new research wave has started to focus on how to enhance smart city approaches as well as sustainable city models by combining these two urban development strategies in an attempt to achieve the required level of urban operations, functions, designs, and services in line with the goals of sustainable development (e.g., Al-Nasrawi et al. 2015; Ahvenniemi et al. 2017; Batty et al. 2012; Bibri and Krogstie 2017a, b; Kramers et al. 2014; Marsal-Llacuna et al. 2015). One implication of this endeavor is that big data analytics and context-aware computing are being given a prominent role, and the evolving data-centric and context-aware approach is seen to hold great potential to address the challenge of urban sustainability under what is labeled "smart sustainable cities" of the future. The way forward for cities to advance sustainability and provide the quality of life to their citizens is through advanced ICT that ensures the utilization of big data and the access to contextual information (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Solanas et al. 2014).

However, the rising demand for big data analytics and context-aware computing as disruptive technologies, coupled with their potential to serve many urban systems and domains, entail significant scientific and technological challenges pertaining to the development of related advanced techniques, methods, and technologies. Such challenges arise from the nature of the big data and context information being generated and captured respectively from heterogeneous and distributed sources. In particular, the scale, variety, complexity, and velocity of big data and context data make them difficult to be managed, integrated, processed, analyzed, interpreted, and deployed for decision-making purposes pertaining to the improvement of urban sustainability.

This chapter explores and reviews the real potential of big data analytics and context-aware computing for improving sustainability in the context of smart sustainable cities. In doing so, it enumerates, illustrates, describes, and discusses the state-of-the-art data-centric and context-aware applications pertaining to diverse urban systems and domains, as well as identifies the key challenges involved and discusses the open issues stemming from these challenges. The main motivation for this chapter is to capture further and invigorate the application demand for the urban sustainability solutions that big data analytics and context-aware computing—as powerful enablers and drivers for the emerging wave of urban analytics and computing—can offer.

This chapter consists of seven sections. Section 9.2 identities and discusses the key differences and commonalities among big data analytics and context-aware computing. In Sect. 9.3, we address the key opportunities and characteristics of big data and context-aware applications in relation to urban sustainability. Section 9.4 enumerates and describes the key applications offered by big data and context-aware technologies in relation to diverse urban domains. In Sect. 9.5, we identify the key challenges involved and discuss the open issues stemming from these challenges. Section 9.6 provides insights into the technological innovation system approach to tackling the current challenges pertaining to big data. Finally, we provide our concluding remarks, contributions, and some final thoughts in Sect. 9.7.

9.2 Key Commonalities and Differences Between Big Data Analytics and Context-Aware Computing

Big data analytics and context-aware computing are advanced, rapidly evolving areas of ICT. They originate in the dominant ICT visions (e.g., the IoT, AmI, UbiComp, SentComp, Cyber-Physical Systems CPS), etc.). Hence, they share basically the same core enabling technologies underlying ICT of pervasive computing, namely sensing devices, (cloud) computing infrastructures, data processing platforms, middleware architectures, and wireless communication networks. There are basically various permutations of the core enabling technologies, which applies to big data analytics and context-aware computing, depending on the scale, complexity, and extension of application domains. Regardless of their number and nature, these permutations fall under ICT of various forms of pervasive computing, most notably UbiComp, AmI, the IoT, SenComp, and CPS, which are associated with smarter cities (ambient city, sentient city, ubiquitous city, etc.) as well as emerging smart sustainable cities (e.g., Bibri and Krogstie 2016a, 2017b). This techno-scientific achievement is expected to drastically change the development of cities in the future. That is to say, the underlying core enabling technologies will be the dominant mode of monitoring, understanding, analyzing, and planning the city to eventually improve sustainability, efficiency, and the quality of life (Batty et al. 2012; Bibri and Krogstie 2016a). However, there exist a vast range of architectures that essentially aim to provide the appropriate infrastructure for big data analytics and context-aware computing as technological systems. And applicable to both is the idea that many heterogeneous computable components (sensor devices, operating systems, information processing units, data repositories, etc.) are spread across diverse networks that interconnect through pervasive computing infrastructures as part of vast architectures enabling data collection and storage, data analysis and management, intelligent decision-support, and service provisioning and application actions (e.g., Bibri 2015a). Important to note is that to facilitate smart sustainable city applications using big data analytics and context-aware computing, the core enabling technologies are required to be coupled, integrated, and coordinated. In other words, a huge amount of computing resources and their seamless amalgamation are necessary to understand, monitor, analyze, and plan smart sustainable cities in order to catalyze and boost their sustainable development process and strategically guide it toward achieving the long-term goals of sustainability. Accordingly, big data analytics and context-aware computing are increasingly being integrated within the smart sustainable city infrastructures to serve a number of urban domains in terms of operations, functions, services, and designs (Al Nuaimi et al. 2015; Bettencourt 2014; Bibri and Krogstie 2017a, b; Marsal-Llacuna et al. 2015).

Unsurprisingly, big data and context-aware technologies also overlap in many computational and analytical aspects, irrespective of the application areas they are applied to. In the realm of smart sustainable cities, they involve such processes as acquisition, storage, retrieval, processing, analysis, interpretation, modeling, and simulation of heterogeneous data to support decision-making and action-taking processes pertaining to diverse urban domains. Other computational processes include search, sharing, integration, transfer, querying, updating, and visualization. Also, the underlying analytics and computing outcomes serve to improve operational functioning, optimize efficiency, enhance the quality of life, and mitigate environmental impacts, all in line with the goals of sustainable development. Important to underscore in this regard is that big data and context-aware applications target, albeit in varying ways, optimization and intelligent decision-support for control, automation, management, and planning purposes through the implementation of optimization strategies and decision-taking processes in relevance to sustainability. Remaining on the topic of applications, and in relation to business domain, context-aware services are associated with "business intelligence applications…which do benefit from a context management infrastructure" (Riva et al. 2005, p. 94), and big data services are at the core of business intelligence in terms of identifying trends, behaviors, and weak spots for making better decisions about the future (e.g., Provost and Fawcett 2013).

One of the key differences between big data analytics and context-aware computing lies in the type of the data to be collected and analyzed in related application areas, with some overlap. Big data entail data of general categories (scientific data, business data, climatic and environmental data, transport data, energy data, waste and water data, traffic data, health data, land use, and planning data). In the realm of smart sustainable cities, this (automated) kind of big data presents us with the ability to use sensors to monitor, track, and integrate a range of data based on the functioning of urban systems and domains and their interrelation. Important to point out here is that these data are not necessarily of a contextual nature in the sense that they pertain to predefined subsets of the context of a given entity at a particular moment as conceived of and applied in context-aware computing. Whereas context data have to be of a contextual nature, i.e., expressing an interpretation of a given situation of urban life (in the form of events, activities, behaviors, locations, environmental states, spatiotemporal settings, etc.), in accordance with the intended use of a particular context-aware application. In the latter case, smart sustainable cities as based on the large-scale and open pervasive computing systems represent forms of computationally augmented urban environments that enable the systems and applications to interact with the surrounding physical spaces, built forms, spatial arrangements, environmental dynamics, infrastructural and operational patterns, and citizens' behaviors in such that they become aware of these contextual features and thus act adaptively and proactively in response to or in accordance with these features, thereby intelligently supporting the urban life in terms of control, optimization, and management as well as the daily activities of citizens in terms of services. Further, one important point to highlight as to the distinction is that, in contrast to big data, which can be real-time, near real-time, periodic, or streams. Context data are real-time (and sometimes near real-time). This relates to velocity as one of the main Vs of big data. Speaking of which, when the context data that are to be collected and analyzed are of huge volume and wide variety, adding to high velocity, we can speak of big context data in terms of Vs.

In addition, both big data analytics and context-aware computing involve the application of the fundamental concepts and techniques of data science—the principles of extracting useful patterns and meaningful correlations from data, including machine learning, data mining, statistical analysis, database querying, and so on, or a combination of these depending on the nature of the application domain. Accordingly, they both use supervised and unsupervised methods as to the creation of different kinds of models. Moreover, the context data collected from the sensors are very diverse (variety) and must be collected and analyzed in real time (velocity) to provide efficient services, in addition to being of huge amount, as so many sensors take measurements every few seconds (volume). In this respect, the 3Vs by which big data is generally defined are of more relevance in the context of health care, education, learning, security, utility, and traffic in terms of large-scale context-aware applications and services within smart sustainable cities. For example, Solanas et al. (2014, p. 76) develop a concept of smart health and define it as "the provision of health services by using the context-aware network and sensing infrastructure of smart cities." Strimpakou et al. (2006) present middleware for context representation and management in large-scale distributed pervasive computing systems, in which huge amount of dynamic contextual information needs to be constantly collected and retrieved, rapidly processed, soundly analyzed, and interpreted, as well as securely maintained in repositories and disseminated. Their framework is a form of hybrid context modeling approach for addressing the heavy requirements of context awareness in open and dynamic pervasive environments as well as context management challenges in distributed pervasive environments. There are several thorough surveys of similar architectures (e.g., Bettini et al. 2010; Perttunen et al. 2009) in terms of scope and complexity, which offer many perspectives and specifics as to the use of context-aware applications in distributed and dynamic pervasive and ambient environments.

In all, big data as a set of advanced techniques and methods serve as an enabling technology for context-aware computing as opposed to being solely a separate technological trend. This pertains to building next-generation context-aware applications for future smart environments such as smart sustainable cities, as such applications involve huge and varied amounts of data that require advanced analytical (computational) systems to be effectively handled in terms of analysis and management. This relates to such socially disruptive technologies or paradigm shifts as AmI, the IoT, and CPS, which will create a wealth of streaming context information. Large-scale context-awareness combining Am and the IoT and big data analytics, in particular, will drive the creation of smarter application ecosystems in diverse urban domains, including energy, transport, built environment, mobility, health, safety, and so on. Likewise, context-aware computing is of fundamental importance to big data analysis and management in terms of exploiting the contextual variables of big data in a bid to enhance monitoring, adaptation, and efficiency of big data processing and analytic systems, especially when it comes to real-time applications where decision-making requires an immediate response.

9.3 Opportunities and Characteristics of Big Data and Context-Aware Applications

9.3.1 The Potential of ICT of the New Wave of Computing Underpinned by Big and Context Data

Irrespective of what notion smart sustainable cities of the future can be based on, whether be it ambient, sentient, ubiquitous, or an Internet of everything, or a combination of some or all of these urban constructs, such cities are said to denote urban spaces loaded with clouds of data intended to shape the operational functioning and the experience of citizens of the city. Here, both big data analytics and context-aware computing are given a prominent role, as all over urban environments, big data, and context-aware applications can monitor what is happening in these environments (as to situations, events, activities, behaviors, locations, spatiotemporal settings, environmental states, etc.), analyze, interpret, model, and react to them at varying ways—be it in relation to smart energy, smart street and traffic lights, smart transport, smart healthcare, smart mobility, smart education, or smart safety—across several spatial scales. In contrast to the prevailing notion of smart cities of the future (Batty et al. 2012), which can “be understood as a collection of plural research traditions, performed and commissioned by divergent actors all with their own motivation and implicit understanding of what a city is or should be” (Shepard 2011), the impetus behind the concept and development of smart sustainable cities of the future—based on the big data and context-aware applications—is to mobilize and align actors for the purpose of promoting and advancing urban sustainability by continuously improving the contribution of these cities to the goals of sustainable development.

Indeed, being varied or manifold, the objectives of big data analytics and context-aware computing are more in conjunction with the goals of the stakeholders that support the integration of these advanced technologies in the urban domain.

The prospect of smart sustainable cities is becoming the new reality (e.g., Al-Nasrawi et al. 2015; Bibri and Krogstie 2016a, 2017a; Höjer and Wangel 2015; Kramers et al. 2014; Rivera et al. 2015; Shahrokni et al. 2015), in particular within ecologically and technologically advanced nations (Bibri and Krogstie 2016a). These techno-urban phenomena are opening up new opportunities for smart cities to explicitly incorporate sustainability and for sustainable cities to improve their contribution to sustainability. Therefore, they are becoming increasingly powerful and established as techno-urban discourses thanks to the advances in several scientific and technological areas in the ambit of ICT of the new wave of computing, notably context-aware computing and big data analytics and their enabling technologies, including embedded systems, multi-sensor data fusion, hybrid modeling and reasoning, machine learning, data mining, cloud computing, middleware infrastructure, and wireless communication networks. Consequently, significant opportunities exist for UbiComp, AmI, the IoT, and SenComp as to their amalgamation in relation to modernizing the sustainable urban model in terms of its various dimensions. Indeed, the range of urban applications that utilize these technologies in connection with sustainability is potentially huge, as these technologies—enabled by big data analytics and context-aware computing techniques, methods, and models—usher in automation in nearly all urban domains and systems (see this chapter for further details). For an overview of application areas of UbiComp, AmI, the IoT, and SenComp in relation to urban sustainability together with the original list of references, the reader can be directed to Bibri and Krogstie (2017b). Worth pointing out in this regard is that a number of application areas of UbiComp pertain also to AmI due to the fact that the concept of AmI is seen to be an extension to that of UbiComp. Likewise, AmI and SenComp application areas also overlap due to the fact that they share the physical environment as a key element of context in terms of their functionalities, as we will elucidate in the next section.

The underlying premise is that there are fascinating possibilities and immense opportunities to realize from deploying the advanced solutions being offered by ICT of the new wave of computing in the context of urban sustainability. This though requires further advancing the available capabilities of big data analytics and context-aware computing in relation to smart sustainable cities. Big data and context-aware technologies and their focused application and use can play a significant role in realizing the goal of these cities as to the improvement of their contribution to sustainability. The synergy between these two advanced technologies and urban sustainability provides insights into understanding the why of directing ICT of the new wave of computing toward sustainable urban innovation. Indeed, the main strength of big data analytics and context-aware computing lies in the high influence they will have on many aspects of smart sustainable cities and on their citizens' lives (e.g., Al Nuaimi et al. 2015; Bibri and Krogstie 2016a; Pantelis and Aija 2013; Solanas et al. 2014).

9.3.2 Demarcation Lines Between the Applications of ICT of the New Wave of Computing

The demarcation lines between UbiComp, AmI, the IoT, and SenComp pertain in large part to the kinds of applications they offer in relation to the domain of urban sustainability rather than in relation to the core enabling technologies which they actually share in terms of sensing, data processing, and networking infrastructures. The underlying distinctions include the way in which the respective applications are used in connection with existing urban domains and subdomains, namely relying on context-aware computing, big data analytics, or a combination of these technologies. Regardless, combining these applications provide fascinating opportunities to advance smart sustainable cities in terms of the processes that operate and organize urban life: physical structures, spatial organizations, infrastructure, administration, ecosystem services, and human services as regards to achieving the goals of sustainable development. Hence, the idea of coupling, integrating, and coordinating UbiComp, AmI, the IoT, and SenComp technologies and their novel applications is invaluable in the urban domain, if not necessary, at the level of big data analytics and context-aware computing with respect to improving urban sustainability. Indeed, efforts emanating from these technological fields modulate and influence every aspect of urban life (Böhlen and Frei 2009). With its varied and overlapping applications, ICT of the new wave of computing can, therefore, add a whole new dimension to urban sustainability as to making the environmental, human, and engineered systems of smart sustainable cities evolve in ways that are more coordinated, efficient, and sustained. Despite their overlapping nature, big data and context-aware applications as enabled by ICT of the new wave of computing still serve one and the same purpose: advancing urban sustainability and integrating its dimensions.

However, recent studies (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a, 2017a; Böhlen and Frei 2009; Kyriazis et al. 2014; Lee et al. 2008; Perera et al. 2014; Shepard 2011; Shin 2009; Zanella et al. 2014) show that most of the applications pertaining to ICT of various forms of pervasive computing, which are based in relation to smart sustainable cities on the notion of an amalgam of infrastructures and services to be directed toward improving sustainability, are still under investigation and development. This is taking place in parallel with the construction of UbiComp, AmI, the IoT, and SenComp landscapes and spaces, which is progressing on a hard-to-imagine scale across many spatial scales and spanning over diverse urban domains. This has been boosted by the recent advancements in several scientific and technological areas within computing, notably context awareness architecture, multi-sensor data fusion, hybrid modeling and reasoning, machine learning, data mining and knowledge discovery, cloud computing infrastructure, middleware architecture, and wireless and mobile networks (Bibri and Krogstie 2016a).

9.3.3 Types of Big Data and Context-Aware Applications

In the context of smart sustainable cities, big data analytics and context-aware computing, which are associated with their operational functioning and planning in terms of efficiency, performance, and the quality of life in line with the goals of sustainable development, involve data processing platforms that handle complex analyses for intelligent decision-support and optimization strategies. These pertain to a wide variety of applications intended for controlling, managing, organizing, and enhancing urban systems, processes, and services in relation to diverse urban domains (transport, mobility, traffic, communication, energy, environment, health care, education, water, waste, land use, public safety, etc.). There are mainly two types of big data and context-aware applications to consider in the realm of smart sustainable cities: real-time applications (e.g., learning, health care, utility, location-based, and web-based information as active applications) and offline applications (e.g., transport, traffic, energy, environment, land use, planning, and design). As to the former, the input is instantaneous or near real-time, the analysis is fast, and system behavior or application action is based on the real-time mining or reasoning capabilities for decision-making since all real-time applications require immediate responses. This implies that if decisions, whether based on the analytical results or reasoned inferences, cannot be made within a specific time line, they simply become of no value or effect. Hence, it is crucial in this regard to provide the kind of data necessary for mining or reasoning in a timely manner and to conduct the analysis or reasoning in a fast and sound fashion for accurate decision-making purposes. As to the latter, the input tends to be periodic and thus analysis occurs sporadically. System behavior or application action comes in the form of delayed responses. For an account of real-time and offline applications relating to smart cities, with a focus on big data analytics, the reader can be directed to Mohamed and Al-Jaroodi (2014).

9.4 Specifics of Big Data and Context-Aware Applications in Urban Domains

In the sequel, we provide some details of the key applications of UbiComp, AmI, the IoT, and SenComp, which rely on the big data and context data as to their functionalities, in the realm of smart sustainable cities of the future. The applications presented here, which pertain to diverse urban domains and thus systems, are by no means exhaustive, and can involve big data analytics, context-aware computing, or a combination of the two. Before we delve into a descriptive and analytical account of these applications, it might be useful to elucidate some relevant relationships.

9.4.1 *The Link Between Big Data and UbiComp and the IoT and Between Context Data and AmI and SenComp*

Big data trends are mainly associated with the IoT and UbiComp technologies (e.g., Batty et al. 2012; Bibri and Krogstie 2017a, b; Chen et al. 2015; Vongsingthong and Smanchat 2014) and context data trends pertain to AmI and SenComp (in addition to UbiComp) technologies (e.g., Bibri and Krogstie 2017a; Böhlen and Frei 2009; Shepard 2011; Solanas et al. 2014), with some overlaps among both of these trends and technologies. The IoT is a form of UbiComp, and AmI and SenComp are two ICT visions that imply a slightly different focus in terms of the concept of context as to its elements or subsets (e.g., Bibri and Krogstie 2016a, 2017b). AmI "should be aware of the specific characteristics of human presence and personalities, adapt to the needs of users, be capable of responding intelligently to spoken or gestured indications of desire." (ISTAG 2003, p. 8) SenComp entails using a sensor infrastructure "to observe and monitor and computing devices to perceive (recognize and interpret) the physical environment and react to it. It is the idea that applications can be made more perceptive and responsive by becoming aware of and responding to their physical surroundings. This also applies to several application areas of AmI" (Bibri and Krogstie 2016a, p. 7). But AmI goes beyond the physical context to include other types of context such as cognitive, emotional, behavioral, social, and spatiotemporal (Bibri 2015a).

With the above in mind, UbiComp and the IoT are likely to deal with more physical objects and thus involve more sensors than AmI and SenComp due to the scale of their ubiquity, and hence, the volume of the data generated is huge and the processes and infrastructures involved in handling these data are complex. Just like UbiComp, the IoT, which "is evolving into more and more sophisticated network of (sensor) devices and physical objects, is estimated to involve all kinds of everyday objects, including people, roads, railways, bridges, streets, buildings, water systems, electrical networks, vehicles, appliances, goods, machines, animals, plants, soil, and air." (Bibri and Krogstie 2016a, pp. 6–7). UbiComp signifies that technology in the form of countless nearby wirelessly interconnected sensors and computers "will permeate everyday human environment and…make everyday objects smart by enabling them to communicate with each other, interact with people and their objects, and explore their environment"; and the IoT denotes "a computationally augmented everyday environment where the physical world (everyday objects) and the informational world (data processing) are integrated within the ever-growing Internet infrastructure via a wide range of active and smart data-sensing devices,", i.e., "the interconnection of uniquely identifiable embedded devices, physical and virtual objects, and smart objects…connected to humans, embedded in their environments, and spread along the trajectories they follow…, [in addition to] embedded systems, intelligent entities, and communication and sensing-actuation capabilities" (Bibri and Krogstie 2016a, p. 6). In the light of these characteristic features, UbiComp and the IoT involve complex sensor infrastructures and networks for the objects involved are boundless. A key significant facet of these two technologies is thus the large number of things that can be connected to mobile, wireless, and Internet networks, each one providing data for a particular purpose. Mechanisms to store, integrate, process, analyze, and manage the generated data through scalable applications remain a major scientific and technological challenge in the ambit of computing, in general, and of big data, in particular. This emanates from the various sensor recording parameters and their length as to the collected and stored data, among other things. The fundamental centralized data processing platforms and data mining architectures remain unfit to computationally and analytically support data stored in distributed sites across pervasive environments. Despite the difficulty of overcoming the hurdles to the wide adoption of UbiComp and the IoT within contemporary cities, they have demonstrated, like AmI and SenComp, distinguished potential to add a whole new dimension to the application and enhancement of sustainability across diverse urban domains by enabling communication between and information exchange among the smart objects deployed in urban environments. Hence, more research in the application of related big data analytics as well as context-aware computing is imperative, and once these advanced technologies are successfully implemented, the benefits and opportunities will be tremendous in the context of smart sustainable cities.

9.4.2 Smart Transport and Mobility

Transport and mobility involve key ICT applications of the next wave of computing. Combined, UbiComp, AmI, the IoT, and SenComp play a key role in improving all forms of transport and mobility in smart sustainable cities. To begin with, the use of the IoT encompasses automated tracking of travelers and their vehicles, monitoring road conditions and traffic jams and providing alerts accordingly, finding parking spaces, road pricing and tolling mechanisms, and safety supervision when distributing valuable goods (Dlodlo et al. 2012; Ghose et al. 2012; Ren et al. 2012; Vongsingthong and Smanchat 2014). In more detail, the IoT devices can assist in interconnecting various aspects of transportation systems (vehicles, infrastructure, drivers, roads, etc.) in terms of integrating communication, management, control, and information processing units across such systems, which results in smart traffic control, road assistance and safety, smart parking, logistic and fleet management, vehicle control, and toll collection systems. Most of these applications are intended to improve environmentally sustainable urban development processes. Likewise, AmI and UbiComp can substantially mitigate the negative impacts of transport on the environment triggered by saturated transport networks, endemic congestion, urban density, and community expansion by providing advanced forms of virtual (simulated) mobility and thus curbing demand for physical mobility (using transport modes). This occurs through retaining an optimum balance between socioeconomic benefits and environmental gains. In this respect, using presence technology (e.g., Bibri 2015a; Riva et al. 2005, 2008) enables highly realistic virtual meetings, virtual teams, virtual communities, virtual worlds, and so on. This pertains to various conceptualizations of presence (when people experience projecting their mind through media to such diverse entities as other people, places, settings, and environments in different x-realities, with the perceptual illusion of non-mediation). For instance, computer-mediated human–human interaction can provide a sense of social richness, realism, immersion, and transportation (Bibri 2015a). In addition, with AmI all people or goods on the move "can be location-aware and communicate with each other. Intelligent objects and networks for logistics can be integrated with intelligent mobile systems for people, creating Virtual Mobile Environments (VMEs). This will address…the seamless services across networks and terminals for nomadic users, limiting the need to travel and optimizing mobility." (ISTAG 2003, p. 10). Furthermore, AmI and UbiComp provide advanced location-based services related to onboard navigation systems (using GPS) that allow, by means of multimedia presentations wirelessly transmitted and displayed on different kinds of mobile devices, effective use of existing transport infrastructure and network. This reduces energy consumption and pollution as well as helps drivers to select cost- and time-efficient driving routes. Through intelligent transport, UbiComp provides potential savings of time and impacts on long-term sustainable land use (Lee et al. 2008). Using onboard driver assistance systems and advanced traffic management, AmI can additionally on the roads "improve the safety of the vehicle, its occupants, and other road users" (ISTAG 2003, p. 11). By also using GPS and the IoT, information can be gathered and predictions be made regarding pollution density to generate localized air quality alerts (Shang et al. 2014). To add, AmI and UbiComp provide services to citizens in relation to the choice of transport modes, which are integrated with each other and with the wider city. Also, through using the IoT and UbiComp, citizens can emit faster and more extensive data of a spatial nature through their use of smartphones, which can potentially enable local authorities in cities to monitor and respond to mobility in a real-time manner. In all, using all forms of ICT of the new wave of computing is aimed at curbing energy consumption, lowering pollution, and eliminating inefficiency being heavily impacted by transport and mobility.

9.4.3 *Smart Traffic Lights and Signals*

To note, the applications presented in this subsection overlap with some of those mentioned above given the synergic relationship between the respective urban domains. AmI, UbiComp, SenComp, and the IoT can, in a complementary manner, provide advantages as too smart traffic lights and signals for controlling the traffic flow in smart sustainable cities. This enhances traffic patterns and conditions and thus transportation, as well as commuting and other forms of mobility. This occurs through handling high volume of traffic congestion (data) by measuring different parameters of the traffic flow (the positions and speeds of vehicle, traffic speed and density, traffic conditions or jams, waiting time at the lights, etc.) using different types of sensors (GPS, loop sensors, remote sensors, etc.). Aggregation and fusion of the measured or collected data and their analysis target intelligent decision-support and optimization and implementation of decision-taking processes and optimization strategies through control in the form of appropriate instructions to be given to the lights and signals or by sending feedback to specific departments to proceed with alleviating potential traffic bottlenecks. For these sensors and computational mechanisms to function properly in terms of providing information about traffic patterns and better services in relation to smart traffic lights and signals, the interconnection of these lights and signals should occur via the traffic grids, data should be collected from all traffic lights across various spatial scales, and intelligent decision systems should be built using real-time big data and context data (e.g., Al Nuaimi et al. 2015).

For instance, AmI and SenComp environments can, based on the dynamic models of traffic sites as physical environments, detect or recognize traffic patterns by analyzing real-time contextual data (number of vehicles at a given moment, physical conditions, spatiotemporal settings, etc.) and then adjust traffic controls accordingly. Additionally, AmI can on the roads "improve the safety of the vehicle, its occupants, and other road users," and "in the air, advances in surveillance and communication in air traffic technologies enable more efficient and reliable air traffic control." (ISTAG 2003, p. 11) The IoT enables "data streaming to process and communicate traffic information collected through sensors, smart traffic lights, and on-vehicle devices to drivers via smartphones or other communication devices." (Al Nuaimi et al. 2015, p. 8). UbiComp also reduces traffic congestion (Lee et al. 2008). By predicting traffic conditions, the IoT can assist in reducing roads' congestion and accidents by opening new roads, directing vehicles to alternative roads, collecting and providing information on parking lots, and enhancing transport infrastructure on the basis of congestion data (Al Nuaimi et al. 2015).

9.4.4 Smart Energy

Using UbiComp and the IoT technologies underpinned by big data and context information can support decision-making pertaining to the supply of power in line with the actual demand of the citizens and the other contextual conditions. Decision makers can base their decisions on real-time data, and energy companies can respond easily to market fluctuations on the same basis. This entails adopting an approach as to when to increase or decrease production, thereby contributing to optimizing energy efficiency. Also, using the same technologies enables the efficient analysis of the big data and context data collected and stored for forecasting or prediction purposes in a near-real-time fashion. Similarly, ubiquitous mobile devices allow citizens to have access to live energy prices and to adjust their use accordingly, thereby reducing stress on the energy costs (as well as on the grid) (Batty et al. 2012). Using specific pricing plans in accordance with supply, demand, and thus production and consumption models is an effective way to align with energy resource optimization as strategic objectives (Al Nuaimi et al. 2015).

In addition, AmI provides great potential to develop environmentally sustainable technologies. According to ISTAG (2003), among the significant opportunities that exist for AmI in terms of environmental sustainability is that it can serve as an instrument in the development of new technologies that optimize energy efficiency and mitigate pollution or risks to health, as well as enable indirect effects by optimizing energy usage and reducing and optimizing physical mobility, to reiterate, that would otherwise lead to more energy consumption at different levels. The IoT provides a lot of potential for optimizing and controlling energy consumption through the integration of sensing and actuation systems (Ersue et al. 2014). As an integrated system, it can include all forms of appliances and energy consuming devices (bulbs, switches, power outlets, etc.) and collect and transfer real-time data to the utility supply companies so they can effectively balance power generation, distribution, and usage (Parello et al. 2014). Moreover, as by-product of their normal operation, the IoT sensors and actuators allow urbanites as users and consumers to remotely control their devices (e.g., electric outlets and switches), as well as provide them with advanced functions like scheduling (e.g., changing lighting conditions), which can also be made available through cloud-based interfaces (Ersue et al. 2014). Among consumer devices that can be controlled for cost-effectiveness and efficiency encompass television, washing machines, bulbs, oven, and water heaters. It is possible now to program intelligent washing machines to run automatically with the cheapest energy rates using AmI (context-aware computing).

9.4.5 Smart Grid

Given the synergy between smart energy and smart grid in the urban domain, some of the applications presented in this subsection overlap with those presented above. With that mind, UbiComp and the IoT allow for observing energy consumption and monitoring GHG emissions in real-time across several spatial and temporal scales so to make them more efficient by curbing energy usage and thus mitigating GHG emissions. This entails that the smart grid collects contextual and big data from diverse power sources and then process and analyze them in real time for decision-making by transmitting relevant information (results and inferences) for process control to improve the performance of the power system (e.g., Yin et al. 2013; Mohamed and Al-Jaroodi 2014). Additionally, the IoT and UbiComp have huge potential for power grid management, as they enable systems to gather and act on near real-time data on power consumption, generation, and inefficiency from end-user connections (information about producers and consumers' behavior), and to manage other distribution automation devices with the aim to improve the efficiency, reliability, and sustainability of power production and distribution (Ersue et al. 2014; Parello et al. 2014). This involves using smart metering infrastructure, including sensors placed on consumers access points as well as on production, transmission, and distribution systems. Smart metering is acknowledged for its efficiency as to monitoring energy consumption for customers. Commonly, self-monitoring and feedback are used as mechanisms as part of deploying smart meters, remote controls, and communication technologies within electricity networks to increase efficiency, reliability, and sustainability. This relates to the idea that distributed energy systems have become self-managing and self-sustaining, and services in the energy market dynamically reorganized and coordinated. Accordingly, there is a tight coupling between the IoT and the energy sector. The IoT can enable new mechanisms for trade on the basis of supply and demand in energy market (e.g., ISTAG 2008). In addition, by providing near real-time data about energy consumption and its patterns, the smart grid enables consumers to manage their usage based on what they actually need and afford, adding to implementing processing to shun potential power outages that might result from high demand on energy, namely dynamic pricing models for power usage; this entails increasing charges during peak times to smooth out peaks and applying lower charges during other times (Al Nuaimi et al. 2015). Incidentally, smart metering is key to avoiding the expensive and carbon-intensive peaks in power grid, using new ways of coordination as to the overall ensemble of consumers; it provides new means for aggregating real-time data on energy consumption and defining dynamic prices schemes (ISTAG 2008). With the roll-out of metering devices and novel software applications, the IoT has made it possible to re-organize and coordinate demand and supply, using new pricing and billing mechanisms, based on the energy market and production. Furthermore, new technologies are transforming the distribution of energy from the broadcasting model to a community-based model (see ISTAG 2008). In relation to renewable energy, advanced technologies enable power grid to "improve planning and coordination around power generation from renewable plants depending on wind or sun. Weather forecast is today so good, that quite good estimations of electricity generation from wind, solar panels, and photovoltaic plants can be made three days in advance…It is well conceivable, for instance to offer a better price for electricity on a windy or sunny day and thus create an incentive to use this carbon neutral energy at a certain time." (ISTAG 2008, p. 7).

9.4.6 Smart Environment

The IoT and UbiComp have great potential to enhance the quality of life of citizens by improving the environment through increasing air quality and reducing noise pollution. This can be achieved by deploying and setting up stations across the city as well as mounting sensors on bike wheels and cars for measuring air quality. AmI can be used to make inferences about the quality of air or the unknown air quality. This can be done by estimating car emissions using floating car data (where cars are at a given moment) as primary sources, which involve individual GPS, Wi-Fi signals, mobile phones, and loop sensors. Then, the outcome can be transferred to the decision-making unit. Zheng, Liu, and Hsieh (2013) suggest a model based on the machine learning and data mining, where diverse types of data, including historical data, human mobility, real-time air data, traffic flow, and road networks, are integrated for further processing using artificial neural networks and conditional random fields. Major achievements are expected by AmI in improving air and water quality, as it "offers the potential to move from traditional monitoring tools to more ambitious end-to-end service delivery development involving advanced forms of decision-support and knowledge management for both pollution prevention and management of resources." (ISTAG 2003, p. 10) The IoT has also the potential for environmental monitoring where sensors can be used for monitoring air quality and atmospheric conditions, thereby assisting in environmental protection (e.g., Li et al. 2011). With using UbiComp and AmI, it is possible to predict future environmental changes based on the spatial and temporal geographic maps, and to detect natural disasters.

9.4.7 Smart Buildings

The IoT and AmI have slightly different uses for building automation systems in terms of managing and saving energy, as they use the same system of sensors and actuators to monitor and control the mechanical electrical, and electronic systems used in residential, industrial, public, and commercial buildings. Their functions relate to Building Management System (BMS), which is "a computer-based system used in smart buildings to automatically control, monitor, and adjust the mechanical and electrical components and devices of heating, ventilation, and air-conditioning (HVAC) systems, lighting systems, home automation systems, power systems, and so on… Its core function is to manage the environment within the building; monitor system performance; manage demand control ventilation; control temperature and minimize heat/cooling losses; monitor carbon emissions levels; manage window and door operations; provide lighting based on an occupancy schedule; and so forth." (Bibri 2013, p. 16). Buildings "offer one of the major sources for reduction in electricity consumption by better monitoring in real-time of the ambient environment through autonomous wireless sensor networks, through smart HVAC systems coupling electronically to weather conditions, to sensor networks and to the presence of people in different rooms,…by using more context-aware technologies" (ISTAG 2008, p. 6). In terms of the IoT, according to Haase et al. (2016), the three main areas covered in the literature are the following:

The integration of the IoT devices with building energy management systems in order to create energy efficient and IoT driven smart buildings
The real-time monitoring for reducing energy consumption and monitoring occupant behaviors
The integration of smart devices in the built environment and their use in future applications.

With such embedded sensors and actuators, digital and physical objects can process information, self-configure, and make independent decisions as to their operational functioning (see Vermesan and Friess 2013). Generally, the IoT applications can configure themselves in reaction to the surrounding (physical) environment, an intelligent behavior that can autonomously be triggered to cope with emerging situations (e.g., Vongsingthong and Smanchat 2014). Objects are said to have AmI capabilities, when they interact with the environment and act autonomously (e.g., Bibri 2015a).

9.4.8 Infrastructure Monitoring and Management

The application of the IoT is associated with monitoring and controlling the operations of urban infrastructures in terms of bridges, railway tracks, and tunnels (e.g., Gubbi et al. 2013). This pertains to any events or changes in the structural conditions of urban infrastructures that can increase risk and cost as well as compromise safety and service quality. In this regard, the IoT devices can be used to improve incident management, enhance emergency response coordination and service quality, and to reduce operational costs in all infrastructure related areas (Chui et al. 2014). The IoT infrastructure, as a by-product of its operation, allows for scheduling repair and maintenance activities in an efficient manner (Bibri and Krogstie 2017b) by coordinating tasks between different service providers and users of these infrastructures and facilities (Ersue et al. 2014). In addition, waste and water management and distribution networks constitute key areas of IoT application in terms monitoring, automation, and optimization.

9.4.9 Smart Public Safety and Civil Security

AmI, SenComp, and UbiComp provide a lot potential to enhance public safety and civil security by using advanced technologies to monitor urban environments, alert citizens of potential risks or threats, and protect public places. There is a sensing and computing infrastructure already installed for handling security, but more sophisticated sensors and information processing systems are being deployed toward the intended monitoring and control to enhance safety and security. AmI offers applications largely based on the providing more security for citizens. In terms of civil security, “AmI has the potential to make an important contribution in…risk assessment and hazard identification involving remote sensing and in-situ intelligent surveillance to inform both the individual and public services; immediate response to perceived threats requiring new decision-support systems capable of processing in near real time huge amounts of data; and damage assessment mechanisms requiring the integration of very high resolution data with cadastral data and decision-support." (ISTAG 2003, p. 10). Sentient technologies can be used for control and security in terms of allowing or denying access to certain citizens to public places as well as preventing potential unrest (Shepard 2011). They "have the affordance to sense who or what is near them and filter this data according to the preferences of its users…and promise that urbanites never have to leave the comfort of being surrounded by like minded people. The other way around: access to certain urban places might only be given to authorized people recognized by embedded sensors." (Shepard 2011). As to UbiComp, pervasive sensors, which detect pollution in the air and water, can help remove many types of pollutants detrimental to pubic health, pervasive surveillance sensors ensure the safety of people at public places, and pervasive sensor networks placed at school zones can protect children from potential danger (Lee et al. 2008). The IoT can help detect or predict natural disasters (e.g., earthquake), which can save many lives and huge resources.

9.4.10 Smart Urban Planning and Design

Sustainable urban planning is the process of guiding and directing the use and development of land, urban environment, urban infrastructure, and the related ecosystem and human services in line with the goals of sustainable development to achieve the required level of sustainability. Smart sustainable urban planning entails the application of advanced ICT as a set of scientific and technical processes to land use patterns, natural ecosystems, physical structures, spatial organizations, natural resources, infrastructural systems, socioeconomic networks, and citizens' services (Bibri and Krogstie 2017a). The development of smart sustainable cities are increasingly relying on data-centric and context-aware applications to help monitor, understand, analyze, and evaluate urban systems across several spatial scales and over multiple time spans so as to improve their performance in line with the goals of sustainable development, thereby effectively and strategically steering urban development toward sustainability. Smart sustainable cities are concerned with the identification of the urban domains associated with sustainability (including transport, energy, environment, mobility, land use, public services, and public safety)—based on the big data and context data—for analysis, interpretation, intelligent decision-support, modeling, simulation, and prediction for the purpose of improving sustainability. This also involves how different components of these domains interrelate and thus affect one another in relation to particular organized and coordinated physical arrangements and spatial organizations in terms of operational functioning and planning. This implies that the management and organization of urban systems and what they entail in terms of operations, functions, and services in the field of sustainable urban planning require not only complex interdisciplinary knowledge, but also sophisticated technologies and thus profound data computation and analytics. Accordingly, big data analytics and context-aware computing capabilities hold great potential to dramatically alter urban functioning and planning with regard to sustainability performance, assessment, and improvement.

The smart sustainable urban planning approach has materialized as a result of the recent shift in smart city approaches—engendered by ICT of the new wave of computing—and in sustainable city models—driven by the application of sustainable development to urban planning. With that in mind, to link the systems of smart sustainable cities to their operational functioning and planning for more effective sustainability outcomes is best to occur through such ICT processes as management, control, optimization, automation, and decision-support. This can be made possible by big data analytics and context-aware computing technologies in terms of extracting useful knowledge and inferring context knowledge based on the computational analytics and understanding directed for decision-making and service provision. Further, smart sustainable cities need to evolve intelligence functions in the form of laboratories for innovation, especially it has become feasible to build dynamic models of cities functioning in real time from routinely sensed data (Batty et al. 2012). Such functions are associated with novel ways enabled by ICT of the new wave of computing as to the efficiency of energy systems, the improvement of transport and communication systems, the efficiency of distribution systems, the optimization of ecosystem provision, the efficiency of human service delivery, and the optimal use of facilities. This relates to the idea of joined-up planning which entails "integration that enables system-wide effects to be tracked, understood, and built into the very responses…that characterize the operations and functions of the city" (Batty et al. 2012, p. 490).

Urban design overlaps with urban planning in terms of perspectives and practices (e.g., Bibri and Krogstie 2017a). In relation to smart urban design and planning approach, Batty et al. (2012) focus in their work on smart (sustainable) cities of the future on ICT in the built environment (buildings, streets, neighborhoods, etc.) and urban design as well as transport, local, metropolitan, and regional planning. In theory, urban design involves urban planning, landscape architecture, and civil engineering (Van Assche et al. 2013), in addition to such substrands as sustainable urbanism, sustainable urban design, and strategic urban design. Smart urban design entails a blend of sciences and artistic architectures which big data as part of urban analytics and related intelligence functions and simulation models are extremely well placed to initiate and contribute to. Urban intelligence functions entail employing the complexity sciences and data science in the process of creating new forms of urban simulation models that provide decisions about urban forms, and hence, generate urban structures and typologies that can improve sustainability and the quality of life (Batty et al. 2012; Bibri and Krogstie 2017a, b). Such models hold great potential to inform future urban designs; the immediacy in constructing such models is being made possible by the real-time city and its sensing infrastructure advancing toward providing data about medium- and long-term changes

(Batty et al. 2012; Bibri and Krogstie 2017b) and their prediction. To note, simulation strategies and prediction methods can be built on top of the mined patterns and generated correlations through the process of knowledge discovery. The emerging models of scientific discovery are germane as to figuring out efficient urban designs (Nielsen 2011). The idea of ICT becoming constitutive and integrative to enhance sustainability performance and generate a better quality of life (or to make urban living more sustainable) is central to the quest for making smart sustainable cities function as a social organism (Batty et al. 2012; Correia and Wuenstel 2011) by design in terms of their physical, infrastructural, operational, and functional aspects.

There are new methods emerging for design and planning driven by the increasing space-time convergence in modern cities. This involves advanced simulation models that inform the design and planning process, which operate at various spatial scales and over different time spans as to predicting changes (and understanding how cities function) in relation to land use, location of physical activities, densification, public transport, and so on, using computer models of various kinds. In fact, the emergence of smart sustainable cities is pushing for more sophisticated simulation models. This is justified by several facts: actions are increasingly complemented by extensive use of ICT, thereby cities shifting away from places and environments dominated by physical actions; automation is ushering in nearly all routine urban functions, thereby computer control increasingly being merged with human actions; the big data provided from these functions offer "the prospect of a world in which the implications of how the city is functioning is continuously available and such immediacy is compressing time scales in such a way that longer term planning itself faces the prospect of becoming continuous as data is updated in real time"; and "the prospect of developing intelligence and planning functions at the same time as the very object that we are concerned with the city is changing its nature due to similar if not the same functions being used in its operation. This kind of space-time convergence in cities implies a level of complexity that only the new and powerful science of the kind that we will pioneer in *future ICT* can address." (Batty et al. 2012, p. 497). All in all, UbiComp, AmI, the IoT, and SenComp are of applicability and relevance to smart urban planning and design.

9.4.11 Smart Education

UbiComp, AmI, and the IoT applications are associated with various public services. These technologies help tailor services to the needs of individual citizens as to healthcare and education (in addition to utility), instead of delivering services in silos, with a one-size-fits-all approach, which still is a daily reality in today's cities. They can be used to integrate the different information systems of service delivery agencies to enhance the quality of life by delivering customizable as well as better and faster services (e.g., Batty et al. 2012; Al Nuaimi et al. 2015; Solanas et al. 2014).

"AmI offers many opportunities, enabling social support systems to be delivered around the clock as befits a 24-h…society" and making possible "to deliver E-Public Service…in a mass customized and location independent way so that E-Public Service can become truly citizen and customer…friendly, anyplace and anywhere." (ISTAG 2003, p. 10), including education. In this context, the use of big data analytics and context-aware computing in relation to UbiComp and AmI, respectively, entails providing advanced solutions for enhancing education processes in terms of efficiency, effectiveness, and richness by means of adaptable, flexible, and relevant services. Within AmI and UbiComp environments, context-aware applications are able to adapt to changing context information gathered from a variety of sources pertaining to education and supported by adequate context information modeling and reasoning techniques on the basis of several subsets of context and their interrelationships (see Bibri 2015a; Bettini et al. 2010). Devising context-aware applications for education using effective, dynamic models are aimed at improving their maintainability and evolvability. This enables to enhance academic knowledge use as well as life-long learning for all citizens. Within the IoT environments, big data applications can optimize assessment methods (e.g., find out whether resources are producing the right results or efficiently allocated) as well as enhance learning attitudes and behaviors by analyzing students interactions with the academic material and reactions to the academic curriculum. The analytical outcome can provide deep insights into new practices and trends on the basis on the data track generated and virtual objects used by students. In addition, big data and context-aware applications allow citizens to actively engage in the kind of leaning environments that are conducive to adaptation to rapid changes of society and what happens around it in terms of scientific paradigms, major intellectual trends, discontinuities, disruptive innovations, technological advancements, and so on. Using big data and context-aware technologies in education has also prospects for, and positive effects on, advancing knowledge, teaching, and learning methods to deliver and receive the right education. This can be achieved by collecting and integrating large datasets pertaining to citizens, infrastructures, entities, and assessment approaches to create a useful resource for analysis and building models that can be used to offer better and more effective education. Especially, big data and context data provide educational organizations with effective tools to personalize and mainstream education as well as to enhance curriculums. For example, UbiComp has great potential to minimize private education cost, to provide life-long education opportunities, and to enable self-learning and creative education (Lee et al. 2008).

9.4.12 Smart Health Care

The improvement of human health is one of the key aims of any advancement and innovation in ICT. One of the major applications of the IoT is medical and healthcare systems. The IoT can provide new forms of health care and enhance medical services. It "involves efficient healthcare systems that provide permanent monitoring, traceability of patients and their medical devices, and full accessibility of their data, connecting medical centers, patients, and doctors with big data repositories and health monitoring software. Therefore, the IoT monitoring devices or specialized sensors (e.g., blood pressure monitor, [blood sugar monitor, sleep pattern monitor] heart rate monitor, temperature monitor, and other vital sign processing devices used to detect anomalies, as well as active and passive RFIDs to gather other kind of patients' behavioral information and detect any change in their normal parameters) enable remote health monitoring systems: monitoring of patients outside of conventional medical or clinical settings, which may decrease healthcare delivery costs, as well as emergency notification systems: methods that facilitate the dissemination of messages to many groups of people alerting or notifying them of an extant or pending emergency situation…. In addition, the integration of clinical devices within living spaces enables patients to use a mobile phone to communicate health data to hospitals or medical centers. Other opportunities for the IoT involve…consumer devices to encourage healthy living, especially for senior or elderly citizens… Solutions for healthcare should encompass such diverse capabilities as: tracking and monitoring, using advanced sensing and communication capabilities; remote services (diagnosis and telemedicine); information management through the value chain; and cross-organization (hospital information systems) integration." (Bibri 2015b, pp. 194–195). One of the key advantages of the IoT as to gathering, monitoring, and analyzing large and real-time data on patients' issues through smart devices (e.g., sensors) accompanying and surrounding patients (home, on the move, etc.) is the provision of accurate, appropriate, and history-aware responses to health issues. Moreover, by its normal operation, the IoT allows for flagging potential health issues frequently or on a demand basis by monitoring, processing, and analyzing complex occurrences and events. In addition, mining DNA of citizens can be used to discover, monitor, and enhance health aspects (Fan and Bifet 2013). More benefits will emerge as more healthcare data are collected and analyzed. About 500 petabytes of healthcare data were generated in 2012, and this is expected to grow to 25,000 petabyte by year 2020 (Khan et al. 2014).

Similarly, one of the significant opportunities that exist for AmI is to provide advanced forms of healthcare and social support. Using advanced computational tools and processes, such as embedded sensors and actuators, simulation models, new forms of database integration, and management and monitoring software, well-being can be improved for all citizens, bringing unprecedented changes in how healthcare can be delivered (Bibri 2015b; ISTAG 2006). Moreover, in terms of support for aged and disabled people, AmI "is a responsive and proactive environment that enables easy participation of the individual in their own healthcare management", and "enables remote monitoring of activity and physical well-being and *e-Inclusion* for people with physical disabilities" (ISTAG 2003, p. 10). A recent study carried out by Solanas et al. (2014) addresses the concept of smart healthcare based on the context-aware computing and thus AmI. As an example to elucidate this concept, "a cyclist wearing a bracelet with accelerometers and vital constants monitoring capabilities has an accident. The body sensor network detects the fall and sends an alert to the city infrastructure. When the alert is received by the system, the conditions of the traffic are analyzed, and an ambulance is dispatched through the best possible route. In addition, the traffic lights of the city are dynamically adjusted in order to reduce the time needed by the ambulance to reach the cyclist." (Solanas et al. 2014, p. 77)

UbiComp can play an important role in transforming mobile computing devices such as smartphones into more what they are originally designed for by providing information to citizens through social media platforms, such as medical advancements and discoveries, new healthcare services and policies, rapid dissemination of diverse information about disease outbreaks. It can also by using better connections and advanced analytics interpret large amounts of the data collected and captured from diverse sources to enhance health outcomes in terms of achieving satisfaction and mitigating error rates (see Batty et al. 2012). While the IoT can track the spread of disease through mobile computing devices, AmI can help predict it based on the identified events, and SenComp can create maps of predicted disease outbreaks based on the data collected through search queries indicating an outbreak based on the geographic location. The IoT and SenComp can also be used to track and predict pollution, respectively, in certain areas based on the data from air pollution monitoring stations (e.g., Zheng et al. 2013, 2014), which can help prevent or mitigate adverse health effects in districts and neighborhoods by alerting or notifying citizens to avoid particular areas. In all, big data and context-aware applications advance healthcare systems by mainstreaming and tailoring care services, enhancing diagnosis and treatment processes, and providing precautionary and proactive care services.

9.4.13 Academic and Scientific Research

Big data applications, enabled by the IoT and UbiComp, are increasingly optimizing academic and scientific research by providing fascinating possibilities to collect and analyze large datasets using powerful machines and sophisticated computational processes. This is projected to lead to new discoveries in diverse fields involving scientific research and innovation, such as applied urban science, environmental sciences, green chemistry, sustainable development engineering, and chemical process engineering. Several engineering domains provide solutions based on the approaches into integrating sustainability analysis to manage human engineered systems by enabling the use of control, optimization, modeling, simulation, and prediction so to develop more sustainable processes of high potential as to the domain of urban planning and development. Especially, the IoT as a form of UbiComp, which "is evolving into more and more sophisticated network of (sensor) devices and physical objects, is estimated to involve all kinds of everyday objects… In short, the connectivity achieved by the IoT involves people, machines, tools, and places. The aim of using the IoT is to achieve different intelligent functions from conducting information exchange and communication to learning about things, identifying things, tracking and tracing things, connecting with things, searching for things, monitoring things, controlling things, evaluating things, managing things, operating things, repairing things, and planning things" (Bibri and Krogstie 2016a, p. 7).

Big data analytics driven by the IoT and UbiComp is changing the paradigm of scientific development, shifting from mainly formulating and testing hypotheses as well as collecting data manually and examining and reflecting on them to relying more and more on data processing, analysis, modeling, simulation, prediction, and verification. Data-intensive scientific discovery is envisioned as the fourth paradigm of scientific development, with the first paradigm being where science used empirical methods thousands of years ago, the second paradigm where science became a theoretical field a few hundred years ago, a process of creating and testing hypothesizes; the third paradigm where science relied on calculation, conducting simulation and verification by computation in recent decades; and the fourth (current) paradigm is where science involves the exploration and mining of scientific data and using data mining techniques to unify theory, simulation, and experimental verification. Indeed, data mining is becoming increasingly one of the most preferred big data analytics techniques for conducting scientific exploration from big data as well as an effective way to solve major issues within many domains. (See Chap. 4 for a detailed overview of the application of this big data analytics technique in the domain of urban analytics in relation to urban sustainability problems). In particular, big data analytics is accelerating and improving how data can be collected, processed, analyzed, modeled, and simulated within academic and scientific research domains so as to make decisions easier to judge, knowledge-driven, and strategic, and hence to support and enhance new practices, strategies, and policies. For instance, big data analytics and related simulation models may completely redefine the problems pertaining to many urban domains and offer entirely innovative opportunities to tackle them, thus doing more than solely enhancing existing practices. Experiences have shown that traditional scientific and academic research paradigms lead to questionable and challengeable assumptions about the evolution of social practices. It may be more beneficial to search for the emergence of new practices around big data analytics and its wider use (in the urban domain). In this sense, new practices can develop around this advanced technology, which can, in turn, be adapted and integrated into these practices, thereby advancing further its use in a way that fits into a wider strategy or formula that makes this technology more meaningful. In all, big data analytics is becoming increasingly a salient factor for academic and scientific innovation with regard to addressing complex challenges and pressing issues, i.e., responding to major environmental concerns and socioeconomic needs. Indeed, the best opportunity for using big data is to harness and analyze data not as an end in itself—but rather to develop big theories about how smart sustainable cities function and can be managed and planned as to their quest for addressing the challenge of sustainability. In this respect, as part of academic and research endeavors, big data analytics can be exploited to reveal hidden and previously unknown patterns and discover meaningful correlations in large datasets pertaining to natural and social sciences so to develop more effective ways of responding to major paradigm shifts and social trends in the form of new processes, services, practices, and policies. In the meantime, to really get a grip on the use of big data to address the challenge of urban sustainability, new theories are necessary. As West (2013) vividly argues, big data require big theories. As to the functioning of cities, discovering patterns and making correlations in big data can only ever occur through the lens of theory (Batty 2013).

9.4.14 The Investigation and Evaluation of the Typologies and Design Concepts of Sustainable Urban Forms

Big data analytics has a lot of potential to, in addition to its uses in all the urban systems and domains of smart sustainable cities for improving their contribution to the goals of sustainable development, accelerate and improve how data can be collected, processed, analyzed, modeled, and simulated in relation to the investigation and evaluation of the typologies and design concepts of sustainable urban forms in terms of the extent to which they contribute to the goals of sustainable development, and what can be done to enhance this contribution (Bibri and Krogstie 2017a, b). With that in mind, big human mobility data can, for example, "be used to overcome the limits of surveys, namely their high cost, infrequent periodicity, quick obsolescence, incompleteness, and inaccuracy" (Batty et al. 2012, p. 489), as well as the constraints and biases associated with several traditional data collection and analysis methods used in the domain of urban planning and development, such as participatory and nonparticipatory observations, interviews, survey questionnaires, and reviews of documents and reports. These issues have indeed long affected the robustness and reliability of research results (theories, generalizations, perspectives, etc.) within the field of urban sustainability or sustainable urban planning. This has in turn impacted on urban practices in terms of the application of the principles and methods of sustainability in the urban domain. Many studies (e.g., Breheny 1992; Cervero and Kockelman 1997; Cheng et al. 2013; Gibbset al. 1998; Kärrholm 2011; Jabareen 2006; Neuman 2005; Williams et al. 2000) investigating, or referring to other research work carried out on, the correlation between travel behavior (walking, cycling, car driving, etc.) and other indicators of environmental performance, on the one hand, and density, compactness, diversity, mixed-land use, and other typologies and design concepts through which sustainable urban forms can be achieved, on the other hand, point implicitly or explicitly to the disadvantages of the traditional data collection and analysis methods and how they affect the value of the obtained research results. These studies usually generate nonconclusive, weak, limited, unreliable, conflicting, or uncertain results. Further, the interested reader might want to read a recent article by Bibri and Krogstie (2017b), where a detailed discussion is provided on several topics related to sustainable urban forms, including, in addition to big data analytics as an alternative to traditional data collection and analysis methods for investigating sustainable urban forms, the role of big mobility data in evaluating the environmental and socioeconomic performances of sustainable urban forms, urban simulation models as an approach into strategically assessing and optimizing the contribution of sustainable urban forms to sustainability, and big data as the basic ingredient for the next wave of sustainable urban form analytics.

9.4.15 Other Smart Applications for Environmental Sustainability

There exist many other smart applications pertaining to environmental sustainability, in addition to the aforementioned big data and context-aware applications. Angelidou et al. (2017) analyze a number of applications addressing environmental sustainability issues that can be found in the Intelligent Cities Open Source (ICOS) community repository (ICOS 2017). ICOS is a meta-repository for smart cities' applications and solutions, addressed to city authorities and application developers with the aim of facilitating the uptake and implementation of smart city solutions (Komninos et al. 2016). Among the smart applications for environmental sustainability identified by Angelidou et al. (2017) include the following:

Big belly Smart Waste and Recycling: A smart waste and recycling system designed for public spaces, comprising modular components that enable cities to deploy waste, recycling, and even compost stations that meet the needs of each station's locations.

Building Energy Benchmarking: A visualization tool that makes it possible for cities to view energy usage for individual buildings. Through maps, charts, and statistics, it is possible to hone in on a region of interest and view energy usage statistics of individual buildings.

DROMS: A demand response optimization and management system, aiming to predict and control millions of connected distributed energy resources across the Internet.

Enovo for Cities: A sensor-based solution that aims to increase efficiency and transparency in waste management. Through tracking container fill-levels and optimizing pickup routes, this solution tries to improve cost efficiency, as well as reduce the environmental footprint of the waste.

Everimpact: An application that monitors the climate in cities to discover the origins of greenhouse gas emissions in cities. It measures and monetizes cities' CO_2 emission by combining satellites and ground sensors' data.

Hoyrespiro: A Web application providing information about city air quality extracted from a city's preexisting environmental monitoring networks. It provides a rapid and effective technological answer to the needs of people with special sensitivity to environmental allergies.

Mapdwell Solar System: An interactive online rooftop solar mapping tool. It allows users to precisely estimate rooftop solar electric potential (PV panels) for almost every building in a given city by a simple click or by inputting an address.

MATSim: An open-source framework to implement large-scale agent-based simulations. Different scenarios can be supported by this model, such as air pollution from traffic, city evacuation in case of emergency, traffic simulation.

Metropia Synergy: An advanced platform enhancing urban transportation system efficiency by influencing personal travel behavior decisions. Using proprietary algorithms and data analytics, it provides a framework to enhance and monitor the transportation systems' performance.

My City 360 – Smart Parking: An integrated solution to the parking search problem. The system consists of a smart app that monitors and controls sensors deployed on the curbside, as well as in garages around town and communicates the information in real time to the drivers.

Openair: A Web-based platform providing a collection of open-source tools for the analysis of air pollution data. It uses the statistical/data analysis software R as a platform, which offers a powerful, open-source programing language ideal for insightful data analysis.

OpenTrip Planner: A multimodal trip planner, which allows users to schedule transit, travel, and map information. It gives detailed step-by-step directions alongside interactive route maps, details of public transport services required and transfer information.

ParkSight: A cloud-based, software-as-a-service (SaaS) application that allows cities access both real-time and historical parking data and aims to make optimal and efficient use of parking resources.

Reroute it: A mobile application to calculate the costs and environmental impacts of transportation choices, combining all modes of transit.

Smart Citizen: An open-source platform for crowd-sourced environmental monitoring. Connecting data, people, and knowledge, its objective is to serve as a node for building open indicators and distributed tools, and thereafter the collective construction of the city for its own inhabitants.

Smart þ Connected lighting: A solution for a powerful light-sensory network (LSN) that gathers a wide variety of data from the environment. These data can support many city services across a common infrastructure: from law enforcement to environmental improvement, transportation oversight, and so on.

Smart þ Connected parking: The solution gathers and delivers the data by combining Wi-Fi infrastructure with IP cameras, sensors, and smartphone apps. It provides visibility into parking analytics, including usage and vacancy periods, which help cities with long-term planning.

Smart þ Connected Traffic: A solution addressing two major challenges for cities: road safety and congestion. It helps the traffic departments accurately detect more incidents, early on, before they become more serious and enables quicker response by monitoring and analyzing traffic flow data.

TRACE: A decision-support tool designed to help cities quickly identify underperforming sectors, evaluate improvement and cost-saving potential, and prioritize sectors and actions for energy efficiency intervention.

TransBASE: An online database and analytical tool that facilitates a data-driven approach to understanding and addressing transportation-related health issues. Using an open-source relational database management system, it aims to inform public and private efforts to improve transportation system safety and public health.

Treepedia: An interactive Web application that measures cities' green spaces. It allows users to view the location and size of their city's trees, submit information to help tag them and advocate for more trees in their area.

Urban Engines: A cloud-based solution providing visibility into transit system performance and commuter. Combining big data and spatial analytics, it attempts to improve urban mobility and help cities make better decisions about transportation.

WasteOS: A dynamic routing system built for the waste management. It uses software and sensors to lower costs of services by building, delivering, and analyzing the most efficient routes for a fleet.

WaterSim: A simulation model created to estimate water supply and demand. Users can explore how water sustainability is influenced by various scenarios of regional growth, drought, climate change impacts, and water management policies.

WaterSmart: A cloud-based platform for data-driven water demand management. It uses data analytics to maximize water-use efficiency and improve financial forecasting accuracy through engaging citizens.

Angelidou et al. (2017) classify the applications according to the environmental issue they address, namely:

High traffic density;
High amount of waste;
Increasing air pollution;
Increasing energy consumption/sinking resources;
Loss of biodiversity and natural habitat; and
Sinking water resources

9.4.16 Large-Scale Deployments

Large-scale deployments of UbiComp, AmI, the IoT, and SenComp are happening across the world, so too is the construction of big data processing platforms and middleware infrastructures for context-aware computing, to improve urban operational functioning, management of urban systems, and urban planning in line with the goals of sustainable development (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a, 2017a, b; Böhlen and Frei 2009; Crang and Graham 2007; Lee et al. 2008; Shepard 2011; Shin 2009; Thrift 2014; Kyriazis et al. 2014;

Solanas et al. 2014). The initiatives of smart cities enabled by ICT of the new wave of computing in several countries across Europe, the USA, and Asia are increasingly considered as national urban development projects that center on strengthening the role of ICT and thereby big data analytics and context-aware computing in sustainable urban development, among other things. This is manifested in the deployment and implementation of sensor technologies and networks, pervasive computing infrastructures, and wireless communication networks in existing urban environments on a hard-to-imagine scale. In the meantime, across the globe, sustainable cities are being planned to be wired, connected, networked, and transformed into a continuous stream of data that can be analyzed and modeled by large machines for a wide variety of decision-making and service delivery processes. Hence, the trend toward smart sustainable cities is underpinned by the recognition that as information processing capabilities become embedded in urban infrastructures, designs, functions, services, and physical objects, cities can get smarter as to increasing their contribution to the goals of sustainable development. Data-centric and context-aware applications and solutions have proven track records for enhancing many sustainability aspects of smart cities as well as for smartening up sustainable cities—thanks to the increasing infiltration of urban environments with big data analytics and context-aware computing as advanced technologies (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Kramers et al. 2014). This implies that the ability of monitoring, understanding, probing, and planning cities can well be leveraged in the advancement of urban sustainability. Therefore, large-scale deployments are increasingly being justified by the benefits that can be gained with respect to the different dimensions of sustainability. Among the applications and services targeted by the ongoing large-scale deployments as to ICT of various forms of pervasive computing include environmental monitoring and protection, noise pollution reduction, transportation efficiency, energy efficiency, water and waste management, building automation, urban infrastructure monitoring and management, traffic management, fleet and logistics management, smart parking, paperless ticketing, health care and social support, learning and tele-working, and public safety.

In all, the application of big data analytics and context-aware computing in smart sustainable cities offers clear prospects for achieving enhanced levels of sustainability in terms of environmental protection, energy efficiency, sustainable planning and design, quality of life enhancement, and well-being. One of the core ideas underlying the use of such advanced technologies is to integrate and harness solutions and approaches through coordinating and coupling urban domains and thereby facilitating collaboration across applications and services to have better and more effective utilization and management of resources and infrastructures, more astutely strategic planning and design, and more efficient and tailored urban services. This is anchored in the underlying assumption that combining big data and context-aware applications involve nearly all urban domains and how their diverse components interrelate in the context of sustainability.

9.5 Challenges and Open Issues

Although the use of big data and context data in urban analytics and planning holds great potential for advancing and accelerating urban sustainability as to its environmental, social, and economic dimensions, and hence, the opportunities for the development of smart sustainable cities of the future based on big data and context data will be enormous, there are significant challenges facing the big data and context-aware ecosystems that need to be addressed and overcome. These challenges pertain to the design, development, and implementation of big data and context-aware applications on a smart sustainable city-wide scale, from heterogeneous hardware and software components through to application actions and service delivery and from data selection, preprocessing, and transformation through to data analysis, interpretation, evaluation, and deployment. Other challenges pertain to the integration, coupling, and coordination of ICT of the new wave of computing. Adding to all these challenges are the environmental risks posed by the massive use of big data analytics and context-aware computing in terms of the underlying enabling technologies (ICT ubiquity) in the context of smart sustainable cities.

9.5.1 Design Science Constraints

From an engineering perspective, big data computing as an ICT field is bounded by the constraints of existing technologies and what this entails in terms of design research outputs, namely representational constructs, methods, models, and instantiations, as well as by design research activities, namely build, evaluate, theorize, and justify, which are being in used for the development of ICT systems and applications (Bibri 2015a). Design is at the core of computing. Design science has its roots in engineering and other applied sciences, which are determining in ICT development, and as a scientific paradigm, it entails an agreed upon set of principles, rules, approaches, and activities used to construct various ICT artifacts to achieve particular goals. However, the prevailing design science paradigm (e.g.,Cross 2001; Hevner et al. 2004; March and Smith 1995) has failed to adapt to the new age of computing, e.g., the amalgamation of recent discoveries in cognitive science and human communication with pervasive computing (e.g., Bibri 2015a). By and large, this paradigm remains locked into a world dominated and driven by what is technologically feasible in terms of engineering, design, and modeling with regard to the machine understandability, processability, and simulation of data. This has implications for the functioning and thus the performance of big data analytics with respect to its applications in a wide variety of domains. Accordingly, there are significant challenges facing the big data ecosystem that need to be addressed and overcome, which pertain to the design, and implementation of big data applications on a smart sustainable city-wide scale, from heterogeneous hardware components through to application actions and from data selection, preprocessing, and transformation through to data mining, simulation, visualization, evaluation, and deployment.

9.5.2 Data Analysis and Management

Big data analytics present numerous challenges that arise from the nature of the data in terms of being large, diverse, and time evolving. Therefore, there is a wide variety of issues that render the data a daunting task to handle as to the use of big data applications in smart sustainable cities. Big data are too massive, voluminous, complex, dynamic, time-related, speed-based, disorganized, distributed, detailed, interrelated, and heterogeneous to be handled by the existing data processing platforms. The processing of this humongous amount of data poses a tremendous challenge to several scientific communities, including artificial intelligence (machine learning), data mining, database architecture, and distributed systems. In view of that, there is a wide variety of issues that render the urban data a daunting task to handle as to the use of big data applications in the context of smart sustainable cities. One significant problem of big data analytics is dealing with the extreme volume of the data that are to be collected, stored, processed, analyzed, interpreted, evaluated, and visualized. In fact, big data have huge potential as long as their size does not become part of the problem (Khan et al. 2014). To put it differently, the scale of the collected data is one of the major problems facing data scientists, as the colossal datasets are usually the one that reaps the most gains due to them allowing the detection of potentially useful patterns pertaining to trends and practices. Also, data come in diverse formats, posing the issue of variety. This relates to the issue of data complexity and the semantic and informational models behind them (Demchenko et al 2013). The ability to extract value from the combination of diverse sources and formats of data is very crucial and intricate. One of the challenges in this regard lies in how we can integrate and analyze structured, semistructured, and unstructured data. This implies that, by deriving from a variety of sources, they can be messy, fragmented, and complex. In particular, the difficulty lies in the integration of the data from a large number of datasources in different formats changing quickly (Krogstie and Gao 2015). This leads to the issue related to velocity. The challenge here pertains to how to create, process, and analyze data against time to produce valuable results, that is, swiftly enough for these data to be used effectively and to avail of their value. In real-time analysis, data may be changing or evolving over time, thereby their recency becoming of more significance than their scale or heterogeneity. In this situation, data analytics techniques are required to detect and adapt to changes first. Big data are absolutely nowhere near to be controlled in this regard, and the same goes for streaming the fast moving data into storage facilities for later processing and analysis. Therefore, it is critically important to find effective ways by devising computationally and analytically powerful mechanisms to cope with fast moving data and their continuous flow in terms of selection, preprocessing, transformation, mining, evaluation, and visualization in order for smart sustainable cities to reap the intended environmental, economic, and social gains and benefits. Toward this end, it is necessary to put in place a cross-service domain system to ensure that access to the data from different urban domains is available at all times in terms of data input and result visualization by the different urban entities involved in the domain of sustainability planning in the ambit of smart sustainable cities. Furthermore, challenges associated with validity and veracity lie in ensuring and maintaining their adequacy prior to data analysis and integration. Any deficiency in validity and veracity can produce erroneous, incorrect, or less valuable results. In addition, it is very difficult to visualize the results in a user-friendly way (Fan and Bifet 2013). In all, there are numerous hurdles to face when it comes to exploiting large amounts of urban data from a computational and analytical perspective.

Notwithstanding the great opportunity for big data analytics in terms of data-centric applications for smart sustainable cities that can offer accurate tools and methods for decision-making and deep insights, the various Vs of big data show clearly how daunting it is to integrate, coordinate, process, analyze, and visualize big data. In the context of smart sustainable cities, the real challenge lies in linking large distributed datasets to make sense of the data as to their utilization for intelligence functions, simulation models, and service delivery systems. Our ability to collect and store data seems to have surpassed our ability to make sense of data, irrespective of the domain to which big data can be applied. This requires, among other things, novel and sophisticated data management techniques and methods (e.g., Xiaofeng and Xiang 2013) to ensure an effective utilization of big data and a proper functioning of analytics. It is though computationally demanding and costly to manage vast, heterogeneous, and continuously changing data by classifying them into a more structured format and make them easily accessible for distributed applications. Existing forms of advanced database management systems (e.g., Michalik et al. 2014) are still inadequate for solving part of the problem. Rarely do data come in a form ordered and processable because of inconsistent data semantics, mismatched data formats, uncontrollable data flow, and misaligned data structures. These issues are most likely to lead to errors and inconsistencies in the data use and consequently lead to incorrect and less valuable results.

All in all, to handle the existing characteristics of big data calls for sophisticated analysis models and powerful management methods—i.e., unconventional tools and techniques. The current situation shows that it will be a long time before standard data processing methods become a reality and eventually mature. Only then can big data evolve into well-behaved forms amenable to analysis and management. Hence, novel methods are needed to efficiently and effectively process, analyze, and manage the colossal amount of data generated routinely from the sensors and other sources widely deployed in smart sustainable cities.

9.5.3 Context Awareness: Design, Engineering, and Modeling

When big data analysis and management methods are applied to distributed and complex context-aware applications due to the high volume, variety, and velocity of the data they involve within the context of smart sustainable cities, the above-mentioned challenges are obviously added to the existing ones in the field of context-aware computing. As a prerequisite enabling technology for ICT of various forms of pervasive computing (e.g., AmI, UbiComp, and SenComp), context awareness already involves enormous challenges that need to be addressed and overcome prior to the development and implementation of context-aware applications for smart sustainable cities. These challenges relate to system engineering, design, and modeling. They include, but are not limited to, the following, to draw on Bibri (2015a):

Paradigms that govern the assembly of context-aware applications pertaining to diverse urban domains and their integration in connection with sustainability, as well as to dynamic models of their knowledge representation and run-time behavior
Tailored methodologies and tools for engineering urban context awareness
General methods for acquiring, storing, processing, analyzing, mining, modeling, querying, and making sense of context data for context-aware applications
The performance of real-time context-aware applications given that they need to be timely in taking actions
Provision of context data as a service to a wide range of applications within diverse urban domains based on integration with the service computing paradigm
Modeling and management of contextual information in large-scale distributed pervasive applications and in open and dynamic pervasive environments (e.g., Bettini et al. 2010; Strimpakou et al. 2006).

Handling context-aware information in smart sustainable cities is a tremendous challenge (see Solanas et al. 2014). Indeed, urban context awareness is a complex, multilevel problem as to its functioning and implementation, from low-level sensor data acquisition, through intermediate-level information processing and modeling, to high-level application action and service delivery.

9.5.4 Privacy and Security

Privacy and security protection is essential in every aspect of social life involving ICT use. Privacy and security issues have been a real dilemma in the realm of ICT for a quite long time. Big data analytics and context-aware computing are thus not immune to these issues. Accordingly, protecting privacy and ensuring security within the infrastructures of smart sustainable cities continue to be an inescapable, tremendous challenge that the ICT research community has to address and overcome. Moreover, the challenge to determine the factors contributing to privacy and security has proven to be of a complex nature. However, it is important to control privacy and security (Forrester Research 2012). It is even more important in the context of smart sustainable cities due to the fact that the gathered information about urbanites is intended to be used for the purpose of improving sustainability and integrating its dimensions. In this context, in which, big data analytics and context-aware computing as ICT areas can be applied to diverse urban domains, privacy and security become a real concern. Privacy and security relate to the sensitive and confidential information stored in diverse large-scale databases pertaining to citizens, communities, organizations, as well as other urban entities such as city authorities, city governments, and urban departments. High levels of security measures are thus required to prevent potential unauthorized use, modification, or deletion of the stored information due to malicious attacks from different sources, thereby protecting confidentiality and integrity (e.g., Bibri 2015b). Therefore, the big data and context-aware applications integrated together across urban domains, agencies, and departments and thus used by multiple entities require high security since the data may move over insecure types of networks, adding to the fact that big data and context-aware technologies today lack sufficient security measures (e.g., Al Nuaimi et al. 2015; Bibri 2015b; Khan et al. 2014; Kim et al. 2014). Notwithstanding the availability of a vast variety of risk management approaches for information security (Fenz et al. 2014), they are only intended to reach an acceptable level of protection against potential threats. Besides, an urban world permeated with a myriad of networked sensors and computing devices raise issues concerning information control and protection on various scales (Bibri 2015b).

By the same token, it is important to prevent encroachments upon and abuses of the privacy of the different components of data-centric and context-aware applications in the ambit of smart sustainable cities, thereby protecting privacy rights of citizens, communities, and organizations alike. In particular, the possibility of inferring citizens' habits, social status, religion, and combining these sensitive variables with healthcare records render the outcome even more delicate, which implies a great challenge that requires a detailed study (see Solanas et al. 2014). There has been an attempt at defining the concept of citizen privacy and providing ways of ensuring its protection (Martínez-Ballesté et al. 2013). Privacy is one of the most contentious issues to deal with when it comes to the use of context-aware computing (e.g., Bibri 2015b), and is greatly threatened by big data analytics (Mann 2012). But keeping on seeking novel ways to address it is definitely worth the effort. Indeed, this is critically important for a successful deployment of big data and context-aware applications in smart sustainable cities of the future. While privacy "is rarely in danger for the data is anonymized through several levels of scrutiny and confidentiality" (Batty et al. 2012), the privacy-enhancing mechanisms proposed thus far remain inadequate to resolve the underlying conundrum (Bibri 2015b). Indeed, privacy-enhancing mechanisms and policies developed and implemented thus far have not gone far in mitigating, not to mention eliminating, privacy concerns in the information society, and this constitutes indeed a major challenge for those who develop and adopt big data and context-aware applications (Al Nuaimi et al. 2015; Bibri 2015b). To further complicate the matters, "the spatial scope and temporal coverage of monitoring activities will be significantly extended and greatly upsurge in AmI and the IoT… The world being filled with smart things—as all-knowing, all-tracing, all-reporting artifacts-is becoming increasingly a disturbing reality." (Bibri 2015b, p. 194) For a detailed account of the risks that ICT of the new wave of computing pose to ethical values in terms of privacy, security, and trust issues, the interested reader can be directed to

Bibri (2015b). All in all, although big data and context data have the potential to add a whole new dimension to how smart sustainable cities function by offering many new opportunities for more informed decision-making and more enhanced practices with respect to our knowledge of how best to guide and plan future cities, there is undoubtedly a dark side to developments in data analytics and data computation in general.

Lacinák and Ristvej (2017) focus their work on the question of the safety and security in smart cities of the future, and also provide some insights into the importance and use of modeling and simulations to address safety issues. Liesbetvan Zoonen (2016) hypothesizes how smart city technologies and big data applications raise privacy concerns among citizens. The general hypothesis of the framework the authors propose offers clear directions for further empirical research and theory building about privacy concerns in smart cities, as well as provides a sensitizing instrument for local governments to identify the absence, presence, or emergence of privacy concerns among citizens. In their work, Khanac et al.(2017) provide a secure service provisioning framework in smart cities. They state that accumulating and processing of various data streams (e.g., citizens' location information, digital engagement, transportation, and environment and local government data) all raise security and privacy concerns. In view of that, they identify a comprehensive list of stakeholders and modeled their involvement in smart cities by using the Onion Model approach, and present a security and privacy-aware framework for service provisioning accordingly. Their framework provides end-to-end security and privacy features for trustable data acquisition, transmission, processing, and legitimate service provisioning, in order to ensure citizens' privacy and guarantee services' integrity. This framework can also be applied to services associated with different dimensions of sustainability (including energy, transport, traffic, mobility, accessibility, healthcare, utility, and public services) in the context of smart sustainable cities of the future.

9.5.5 Urban Growth and Data Growth

People in smart sustainable cities affect and are affected by big data and context-aware applications. In particular, the urban population size has a great impact on the size of big data and context data. That is, the amount of data generated (big data) and data captured (context data) rapidly grow and thus become complex as a result of the population growth. This requires big data and context-aware applications to be designed such that they are evolvable and extensible in response to new urban conditions and dynamics in terms of the complexities, interconnections, and behavioral patterns pertaining to urban systems and processes in the context of sustainability. By being able to evolve quickly and extend efficiently, these applications can handle particularly the increasing volume and variety of big data and context data to help avoid the problems associated with urbanizations and affecting sustainability. This is an enormous challenge to face with respect to the computational, analytical, and technological features of the ICT infrastructures of smart sustainable cities as well as traffic congestion, energy inefficiency, pollution, and social inequality engendered by urbanization. The desired evolvability and extensibility of big data and context-aware applications are hence meant to overcome environmental pressures and thresholds and changes in socioeconomic needs and concerns. The basic idea is that adopting more sophisticated computational techniques, data processing platforms, and dynamic and simulation models with regard to big data analytics and context-aware computing technologies and their applications have great potential to, no matter how exponentially data will continue to grow, mitigate the adverse (multidimensional) effects that smart sustainable cities might encounter as a result of stretching beyond the capacities and designs of urban systems (e.g., physical forms, infrastructures, ecosystem services, human services, and administration) accompanying urbanization. Otherwise, the environmental, economic, and social development processes of smart sustainable cities are likely to be jeopardized due to the problems caused by urbanization and their direct implications for inappropriate big data and context-aware applications. The ultimate goal is to design, develop, and deploy smart sustainable cities in ways that enable the related technological platforms and applications to be flexible, scalable, and dynamic enough to deal with the growth of big data and context data in order to sustain the momentum for improving different dimensions of sustainability as well as efficiency and the quality of life through effectively analyzing and interpreting the collected data to obtain valuable results and generate accurate inferences and thus enable intelligent decision-support in line with the goals of sustainable development.

9.5.6 Data Quality

To make sense of data proliferation, it is important to establish standards for ensuring that quality standards are attained on several scales. Data quality is a crucial aspect of all kinds of big data applications, but is considered even more important for smart sustainable city applications because decision-making processes are associated with different dimensions of sustainability and their integration. Establishing standards entails assessing truthfulness and accuracy in big data, a feature which relates to the attributes of veracity and validity, respectively. In this regard, the challenge lies in how to guarantee the meaningfulness and relevance of the results obtained from data analysis and interpretation in the context of sustainability. Failing to address this challenge is most likely to affect the value of the data, among others in terms of their worthiness and usefulness when these data turn into useful knowledge and thus become determining in decision-making processes associated with sustainability. In addition, data captured by different urban entities and stored in databases are rarely based on the established standard formats (Lee et al. 2013). A corollary to relying on data from multiple urban entities not complying with established standards is the lack and misalignment of data structures, thereby, the inconsistency, incompatibility, heterogeneity, and incorrect arrangement of the data. Furthermore, there is a lack of standardized criteria or metrics when it comes to retrieving and transforming the data into a unified data source or compatible format prior to data analysis and interpretation (Lee et al. 2013). In addition, the issues related to the uncertainty and incompleteness of the data are common due to sensor inaccuracy, faultiness, and calibration inadequacy, coupled with the nonhomogeneity of urban space, which may introduce errors and inconsistencies between the urban environment and urban dynamic and simulation models. As sensors are crucial for building and maintaining dynamic models (as well as simulation models) in the ambit of smart sustainable cities, they are most likely to affect the performance of big data applications. To put it differently, any sensor deficiency carries over its effects to the process of data analysis and interpretation and thus to decision-making processes due to the inherent errors and inconsistencies in the data collected routinely by various forms of sensors, especially when it comes to real-time applications. This is anchored in the underlying assumption that dynamic models are seen as a concrete interpretation of the physical environment within the context of smart sustainable cities, and conceptually stand between the urban environment and the abstract notion of these applications. Indeed, big data applications interact with the urban environment by monitoring and understanding their surroundings, which is attained by a sensor infrastructure and network that serve to maintain models representing the states of the dynamically changing urban life. Hence, it is important to ensure the abstract notion of the domain of application is compatible and consistent with the concrete dynamic model, especially big data applications operate in distributed, dynamic, and heterogeneous environments and thereby need to interact seamlessly across several urban domains with different concrete models. Likewise, urban simulation models, which are intended to inform future designs of smart sustainable cities, are constructed through pervasive urban sensing which provides data about medium- and long-term changes. In all, it is valuable and necessary to set policies to ensure high data quality, to update data collection and usage policies in a continuous manner, to ensure urban actors understand and comply with these policies, as well as to implement data documentation standards pertaining to the guidance on the use of datasets (Bertot and Choi 2013).

9.5.7 Data Sharing

A key challenge arising from the use of big data and context data is information sharing among different urban departments in the context of smart sustainable cities. This is still contingent upon the way in which these cities are ecologically governed and economically structured within a given nation. This determines to a great extent how the city governments are willing to put their warehouse or silo of information accessible to the public for the benefits of advancing sustainability, unless the data are governed by certain privacy conditions (citizens' rights of privacy). This may render these data hard to share across different urban departments, e.g., health care and medical records, which in fact applies to some big data and context-aware applications. As noted by Solanas et al. (2014), the ability to gather unprecedented amounts of information in the case of context-aware health could threaten the privacy of citizens, despite the potential of smart health to mitigate many health-related issues. Regardless, it is crucial to find alternative ways to reduce the hurdles to achieving seamless information sharing among different urban entities when the improvement of urban sustainability becomes the purpose of this information sharing. The challenge simply lies in ensuring big data can be shared to the extent the citizens (individuals and communities) wish and no more. Though not crossing the line between collecting and analyzing big data and context data and ensuring citizens' rights of privacy is not an easy task (see, e.g., Solanas et al. 2014; Su et al. 2011). Therefore, smart sustainable cities will need to device relevant governance models, mechanisms, and policies as ways to mitigate the potential hurdles hampering the seamless sharing and exchange of information among different urban departments (e.g., Su et al. 2011).

For a detailed account of other types of challenges pertaining to big data analytics, the interested reader can be directed to Katal et al. (2013); Kaisler et al. (2013); Kitchin (2014); and Townsend (2013), among others.

9.5.8 Controversies

Big data contain a wealth of rules and useful knowledge, which are not given directly and cannot be fully utilized. To mine these rules and knowledge from big data require addressing issues pertaining to not only data selection, semantic description, and semantic interpretation, which can directly be applied to big data, (DeRen et al. 2015; Tantatsanawong et al. 2011), but also to uncertainty and incompleteness as to data generation and representation. In their prototype implemented using the Hadoop architecture for big data analytics for smart cities on the basis of cloud computing infrastructure, Khan et al. (2015) apply a priori technique, a rule based data mining algorithm, to learn rules from an open dataset. However, increasing data uncertainty is most likely to result from the increasing volume of the data and the speed at which they need to be processed and analyzed (e.g., Malilk 2013). Incidentally, semantic interpretation relates to a data value, as it deals with the interpretation of ambiguous and imprecise data. Other controversies over the use and benefit of big data analytics within smart sustainable cities relate to inadequate available techniques, representativeness, accuracy, limited access and related divide, and ethical concerns about accessibility (e.g., Fan and Bifet 2013). These issues have implications for the performance of data-centric applications pertaining to the domain of urban sustainability. Therefore, it is necessary to advance and regulate the existing range of big data analytics models in relation to various urban domains (e.g., energy, environment, transport, traffic, land use, planning, public health, and public safety) and how some of these domains may join up in the context of sustainability in the realm of smart sustainable cities. Besides, from an analytical perspective, many sustainability issues have not hitherto been effectively addressed, including public health, energy, environment, disaster forecasting, water resources, and biodiversity (DeRen et al. 2015). All in all, a number of technologies involved in the management, analysis, migration, integration, integrity, discovery, coordination, and consumption of big data are immature and not yet convincing. And it will be a long time before standard data processing tools and management methods become a reality and eventually mature. Only then can big data evolve into well-behaved forms amenable to analysis. From a social perspective, Kitchin (2014) provides a critical reflection on the implications of big data and smart urbanism, examining five emerging concerns: the politics of big urban data, technocratic governance and city development, corporatization of city governance and technological lock-ins, buggy, brittle and hackable cities, and the panoptic city.

9.5.9 Cost and Deployment

Big data and context-aware technologies involve financial challenges due to the high cost associated with their development and implementation. Data-centric and context-aware applications for urban sustainability entail new advanced technological systems that may be very expensive to deploy, test, and operate, and that can evolve as part of large-scale urban projects in terms of the required resources due to their extension and complexity. Across the globe, governments are concerned about the cost of implementing smart sustainable cities based on the big data as national urban projects due to the needed financial and regulatory capabilities as well as the available resources, which represent enormous challenges and potential bottlenecks involved in the process of developing and sustaining these cities. There can be a sustainability issue here in the sense that even technologically and economically advanced nations where data and computing and financial resources are abundant, data science can still be resource-intensive and money-consuming. For example, while the cost of big data storage is decreasing due to recent advances in storage technology, there are still some challenges when it comes to storing big data in compliance with the established standards for storage of large datasets, as constructing storage facilities or repositories in accordance with standard rules requires huge budgets. Indeed, some smart cities tend to opt for reduced quality of data storage to reduce costs (e.g., DeRen et al. 2015). Nevertheless, as pointed out above, large-scale deployments of UbiComp, AmI, the IoT, and SenComp and thus the construction of big data analytics platforms and context-aware computing infrastructures are happening across the world to improve operation, management, and planning in line with the goals of sustainable development, among other things. In the meantime, while financial issues tend to hamper some smart cities from transitioning into smart sustainable cities, there are sustainable cities that are undergoing a high level of smartness by planning nearly everything to be networked, connected, and transformed into a constant stream of data that enable urban environments to be monitored, understood, analyzed, and planned to improve sustainability. This is underpinned by the recognition that data science is an important tool and sustainable approach, thereby, the pursuit of the necessary resources and alliances by city authorities.

9.5.10 Coupling, Integrating, and Coordinating ICT of the New Wave of Computing

The opportunities for smartening up (the redevelopment of) sustainable urban forms (compact city, eco-city, new urbanism, and green urbanism) using ICT of the new wave of computing at every spatial scale will be enormous in terms of advancing sustainability. However, the real challenge lies in, on the one hand, putting in place novel digital technologies that will couple, integrate, and coordinate UbiComp, AmI, the IoT, and SenComp with regard to the underlying core enabling technologies that are fast proliferating and, on the other hand, merging UbiComp, AmI, the IoT, and SenComp with the typologies and design concepts of sustainable urban forms. (See Bibri and Krogstie (2017b) for a detailed overview of this urban endeavor). For there to be concrete synergy in terms of the amalgamation of ICT of the new wave of computing with the strategies through which sustainable urban forms can be achieved, the idea of smart sustainable urban forms with all its enhanced environmental gains and socioeconomic benefits will only turn into reality if such coupling, integration, coordination, as well as merger are specifically addressed, with sustainability in mind as a guiding and organizing principle. This will necessitate entirely unconventional and diversified tools, methods, and models for collecting, processing, analyzing, synthesizing, and modeling diverse urban data and transforming them into useful knowledge for decision-making purposes directed toward not only catalyzing and boosting the sustainable development processes of these urban forms, but also strategically assessing and maintaining their contribution to the goals of sustainable development and hence advancing sustainability. These tools, models, and methods are yet to be addressed, exploited, and extended. This involves a blend of sciences (e.g., data science, computer science, complexity science, and sustainability science) and city-related disciplines (e.g., urban planning, urban design, and urban sustainability). Needed mostly prior to this is a clear synthesis of ubiquitous sensor infrastructures, data processing platforms, middleware architectures, wireless communication networks, large-scale and integrated databases, and data storage facilities, coupled with institutional and policy apparatuses and organizational techniques that can relate to the major challenges of sustainability in the realm of sustainable urban forms. This, in turn, signifies a paradigm change as to how to address environmental and socioeconomic challenges such forms continue to face, using ICT of the new wave of computing and capitalizing on its innovative and disruptive power yet to be unleashed. This paradigmatic shift will pave the way for finding the more effective means to steer technological progress in a direction where its rapid pace will no longer happen ad hoc, when new technologies and their applications become available, but will be grounded in a rather focused overall approach driven by the application demand for the most needed solutions for urban sustainability that future ICT can offer, that is, motivated by a realistic tackle of the most pressing environmental and socioeconomic urban issues. The smart sustainable urban form will be in the vanguard of this macro-shift or techno-urban change.

9.5.11 *Environmental Risks Posed by ICT of the New Wave of Computing*

The prospect of smart sustainable cities is becoming increasingly the new reality with the massive proliferation of data sensing, data processing, pervasive computing, and wireless networking technologies across urban systems and domains. In other words, smart sustainable cities typically rely on the fulfillment of the prevalent ICT visions of the new wave of computing. In view of that, it becomes inescapable to avoid the multidimensional, adverse effects of ICT on the environment. Due to the scale of its ubiquity presence and massive use, future ICT in its various forms shaped by the increasing application of, and driven by the growing demand for, big data analytics and context-aware computing as a set of novel technologies has a number of risks and uncertainties in relation to environmental sustainability that need to be understood when placing high expectations on and marshaling huge resources for developing, deploying, and implementing smart sustainable cities and their advanced applications. There exist intricate tradeoffs and relationships among the positive impacts, negative effects, and unintended consequences of ICT in relation to the environment (Bibri 2015b)—flowing mostly from the design, development, use, application, and disposal of UbiComp, AmI, the IoT, and SenComp technologies throughout smart sustainable cities. As argued by Bibri and Krogstie 2016a, p. 26), "it is difficult to estimate the potential of ICT for environmental sustainability in a…meaningful way in the realm of smart sustainable cities, as advanced ICT solutions involve technological innovation systems embedded in much larger socio-technical systems in which a web of factors and actors other than merely scientific and technical potential come into play… ICT sector own emissions are increasing due to the growing demand for its advanced applications and services, especially those being offered by UbiComp, AmI, the IoT, and SenComp… The adverse environmental effects of new technologies are complex and intricate." They include constitutive effects, rebound effects, indirect effects, direct effects, and systemic effects. For a detailed account and discussion of such effects, the reader can be directed to Bibri and Krogstie (2016a). Again, it is very challenging, if not daunting, to evade the conflicts among the goals of sustainable urban development. In view of that, as argued by Brown (2012), sustainability science must involve the role of ICT in aggravating the unsustainability of social practices (e.g., urban planning and development), just as in tackling the complex problems (e.g., environmental risks) such practices generate. In all, unless smart sustainable cities can "be reoriented in a more environmentally sustainable direction, as [they] can not, as currently practiced, solve the complex environmental problems placed on their agenda" (Bibri and Krogstie 2016a), they risk becoming fallacies or paradoxes in the long term. ICT solutions should in this regard be carefully implemented in conjunction with other measures as well as policy and planning instruments to yield the desired outcomes as to the environmental gains and benefits expected to result from the development and implementation of smart sustainable cities of the future. Toward this end, it is important to underscore from the perspective of smart sustainable urban development that for advanced ICT solutions to function constructively, a concerted action is required, which should be guided by coordinating bodies and mayoral institutions with relevant governance roles as well as expert knowledge in order to strategically assess the implications of ICT investments in this direction, and thereby steer ICT innovations in ways that align with the agenda of sustainable urban development toward achieving the long-term goals of urban sustainability within ecologically and technologically advanced nations (Bibri and Krogstie 2016a).

9.6 On the Technological Innovation System Approach to Tackling the Current Challenges

For smart sustainable cities to be able to achieve the desired outcomes from applying and using big data analytics and context-aware computing in relation to sustainability, the associated applications pertaining to diverse urban domains are required to be supported by cutting-edge and sophisticated techniques, methods, and models, ideally standing out as unconventional renditions in the ambit of computing, that can enable large amounts of data to be integrated, structured, coordinated, managed, analyzed, and modeled more efficiently and effectively for obtaining valuable results and strong inferences necessary for supporting reasonably accurate and timely decision-making processes. To put it differently, by understanding, exploiting, and extending, or simply advancing knowledge on, the available computation, analysis, and management capabilities associated with big data analytics and context-aware computing in terms of conceptions, tools, principles, paradigms, methodologies, and risks, great opportunities can be realized in terms of improving, harnessing, and integrating urban systems and thus facilitating collaboration, coordination, and coupling among urban domains through data-centric and context-aware applications in the context of smart sustainable cities. It is safe to say that as long as big data and context data in urban analytics are driven by sustainable development agenda and thus utilized and implemented strategically for the purpose of monitoring, understanding, probing, and planning smart sustainable cities, ICT of the new wave of computing will drastically change the way such cities function as to increasing their contribution to the goals of sustainable development over the long run. This requires the current open issues stemming from the aforementioned challenges to be under rigorous investigation and scrutiny by the socio-technical systems involved in the underlying technological innovation system of big data analytics and context-aware computing, namely industry consortia, business communities, research institutes, universities, policymakers and networks, and governmental agencies. A technological innovation system refers to "socio-technical systems focused on the development, diffusion, and use of particular technologies" (Bergek et al. 2008, p. 408). In other words, it denotes a dynamic network of actors interacting within a specific industrial sector (e.g., urban industry domains) under a particular institutional set-up (governmental agencies, policymakers, public research institutes, etc.) in the production, diffusion, and utilization of new technologies (e.g., Carlsson and Stankiewicz 1991; Carlsson et al. 2002), e.g., big data analytics and context-aware computing for smart sustainable cities. As proposed in the literature on socio-technical systems (e.g., Geels 2004), new technologies are seen as systems of socio-technical elements interacting with each other, and this approach provides insights into understanding the development of new technologies. Accordingly, the involved social and technological actors ought to work together and take a holistic view of the issues of sustainability within the context of smart sustainable cities which indeed represent sets of techno-urban innovation systems resulting from the dynamic network of relationships among these actors. Moreover, the socio-technical system approach to innovation system entails the socio-technical elements needed to fulfill a certain societal function (Bijker 1995; Geels 2004). The typically complex, diverse sets of socio-technical systems underlying smart sustainable cities involve different innovation entities operating at the intersection of technological development and urban development across many urban domains for the purpose of advancing sustainability and integrating its dimensions as a societal function (Bibri and Krogstie 2016a). Conceptualized as an interplay between scientific innovation, technological innovation, environmental innovation, urban design and planning innovation, institutional innovation, and policy innovation, smart sustainable cities represent and involve inherently complex socio-technical systems of all sorts of innovation systems. Such systems, which focus on the creation, diffusion, and utilization of knowledge and technology, are of various types (variants of innovation models), including national, regional, sectoral, technological, Triple Helix of university-industry-government relations, Quadruple Helix of university-industry-government-citizen (Bibri and Krogstie 2016a). In the literature, innovation models have been approached from different perspectives (e.g., Marinova and Phillimore 2003; Lindell 2012). For example, Marinova and Phillimore (2003) provide a historical examination of innovation models which are used to explain innovation as a process generating new products and methods (e.g., ICT solutions and approaches for urban sustainability) in terms of the activities and stakeholders involved (e.g., urban activities and urban actors). To reiterate, of all the introduced innovation models, the technological innovation system is of prime focus here in terms of explaining why and how new technologies for urban sustainability have been developed, diffused, and utilized in the context of smart sustainable cities within ecologically and technologically advanced societies. And such system is part of a wider theoretical approach to innovation system whose core idea, which explains the rate, nature, and direction of technological change, is that the determining factors thereof are not only to be found in industrial firms, firms of expertise, industry consortia, and research institutes and universities, but also in the wider societal structures where such firms, consortia, and institutes are embedded. For further discussion, the reader can be directed to Bibri and Krogstie (2016a).

Lastly, it is of critical importance to overcome the challenges to big data analytics and context-aware computing prior to the deployment and implementation of the associated applications within smart sustainable cities of the future, especially both smart cities and sustainable cities are already dealing with complex challenges and pressing issues associated with the incorporation of and the contribution to the goals of sustainable development, respectively (Bibri and Krogstie 2017a).

9.7 Conclusions

Big data analytics and context-aware computing are rapidly growing areas of ICT that are becoming ever more important to smart sustainable cities. These concepts were crystallized into realist notions in the domain of sustainable urban planning not too long ago—when UbiComp, AmI, the IoT, and SenComp as the most prevalent ICT visions of pervasive computing have become achievable and deployable paradigms and thus matured due to the advance and prevalence of sensor technologies, cloud computing infrastructures, middleware architectures, data processing platforms, and wireless communication networks. This major technological transition is drastically changing how cities can be understood, monitored, analyzed, and planned to improve their contribution to sustainability under what is labeled “smart sustainable cities” as future techno-urban visions. In light of this, smart sustainable cities have the potential to leverage their informational landscape by deploying and implementing a variety of smart applications based on the big data analytics and context-aware computing as key strands of ICT of the new wave of computing to enhance their operations, functions, services, and designs in line with the goals of sustainable development. To put it differently, big data analytics and context-aware computing and their uses will play a significant role in realizing the key characteristics of smart sustainable cities, namely operation and service efficiency, life quality enhancement, natural resources optimization, and infrastructures and facilities management. Indeed, huge expectations for gains are being placed on the ongoing research within big data analytics and context-aware computing in the ambit of urban computing and ICT. This is justified by the opportunities created by their amalgamation with regard to the improvement of urban sustainability. Worth reiterating is that their effects in this regard reinforce one another as to their efforts for transforming the processes operating and organizing urban life by employing and merging data-centric and context-aware applications to improve, harness, and integrate urban systems as well as to facilitate collaboration and coupling among diverse urban domains.

The aim of this chapter was to explore and review the real potential of big data analytics and context-aware computing for improving urban sustainability. In doing so, we enumerated, illustrated, described, and discussed the state-of-the-art data-centric and context-aware applications pertaining to diverse urban systems and domains, as well as identified the key challenges involved and discussed the open issues stemming from these challenges. The role and significance of big data analytics and context-aware computing are evident not only in terms of catalyzing and boosting the development processes of smart sustainable cities, but also in terms of understanding, monitoring, analyzing, and planning such cities in ways that strategically improve their contribution to sustainability. Big data and context data directed for urban analytics entail a blend of advanced applications, services, and computational and analytical capabilities enabled by constellations of instruments across many spatial scales linked via multiple networks, which can provide a fertile environment conducive to realizing the long-term goals of sustainability. In particular, big data and context-aware applications have the potential to serve a wide variety of urban domains as well as to add value to how their diverse components and entities interrelate with respect to operation, management, and planning in a more sustainable direction. The key applications enabled by big data analytics and context-aware computing include smart transport, smart energy, smart environment, smart planning, smart design, smart grid, smart traffic, smart buildings, smart education, smart healthcare, and smart safety. Advanced technologies can be highly useful when considering the intelligent management and planning of the infrastructure, natural resources, and facilities of the city as well as the improvement of its physical and spatial forms and the quality of life of its citizens, with the ultimate goal of improving sustainability (see, e.g., Batty et al. 2012; Bibri and Krogstie 2017a, b; Kramers et al. 2014). Local governments in ecologically and technologically advanced nations are investing in new ICT to equip cities with technological infrastructures capable of supporting big data analytics and context-aware computing (Al Nuaimi et al. 2015; Solanas et al. 2014), actively engaging in smart sustainable initiatives and projects in the hopes of reaping sustainability benefits by means of developing and implementing data-centric and context-aware applications across existing and new urban environments.

With their different levels of success and maturity, big data and context-aware applications presented in this chapter can be considered mainly as guides to encourage endeavors toward the development of smart sustainable cities of the future and thus stimulate large-scale deployments. Currently, cities around the world badging or regenerating themselves as smart sustainable utilize big data and context-aware applications for handling basic routines in relation to urban systems, and related projects are still very few and scattered. What is rather needed at this stage is to develop comprehensive and integrated frameworks that enable to integrate the existing applications associated with different dimensions of sustainability prior to making any decision about large-scale deployments in order to effectively advance urban sustainability. In other words, it is essential to have a holistic strategy for smart sustainable cities that go beyond an archipelago of unconnected projects, islands of separated applications, or stand-alone initiatives, where all kinds of requirements and objectives should be considered and scrutinized. This holistic approach will help give a clear view of what is needed in terms of resources, finances, and competencies, and eventually will lead to well designed and deployable solutions for smart sustainable cities. Accordingly, any future investment should be focused and justified enough to support the endeavors of the design and implementation of data-centric and context-aware applications throughout the various stages of the development of smart sustainable cities. Without this, the full benefits of such cities cannot be gained nor can the envisioned plans be realized with respect to the improvement of urban sustainability.

Furthermore, just as there are many opportunities and prospects ahead to embrace, there are challenges ahead to address and overcome. These challenges are of computational, analytical, and technological kinds. They include design science constraints; data management and analysis; context awareness design, engineering, and modeling; privacy and security; urban growth and data growth; data sharing and quality; cost and deployment; controversies; and coupling, integration, and coordination of ICT of the new wave of computing. While many of the related open issues are currently under investigation and scrutiny by industry, research, and technology policy communities, deploying and implementing big data and context-aware applications for smart sustainable cities of the future require further addressing and overcoming other organizational, institutional, ethical, and regulatory challenges (e.g., Al Nuaimi et al. 2015; Batty 2013; Bibri 2015b; Kitchin 2014; Townsend 2013). It is worth noting that these challenges are most likely to have varying implications with regard to big data and context-aware applications and to involve different levels of complexity, as they relate to diverse urban domains that are associated with different dimensions of sustainability and different kinds of applications, which require rather immediate and accurate responses. Regardless, novel and sophisticated methods and techniques are needed to effectively process, analyze, and manage the colossal amount of data generated routinely from the sensors widely deployed across smart sustainable cities. Toward this end, and thus to address a majority of challenges facing big data applications in such cities, the efforts should be focused on advancing machine learning, data mining, database architecture, and distributed systems as multidimensional and multidisciplinary spheres. At this stage, the research endeavors in smart sustainable cities should be directed toward improving the early stages of processing big data (selection, preprocessing, and transformation) to facilitate the latter stages of processing colossal datasets (data mining, evaluation, and visualization), as the former stages hamper the progress toward the latter stages (see Chap. 4 for a detailed account of all stages).

As it has proven to be a worthy endeavor to amalgamate big data analytics and context-aware computing in the realm of smart sustainable cities of the future, more rigorous, intensive research within these two ICT areas is highly encouraged, if not imperative, given the underlying promising and rewarding potential. Indeed, the emergence of big data and context-aware technologies has provided diverse research opportunities for developing advanced solutions to some of the most significant challenges and pressing issues pertaining to diverse urban domains. In view of that, we consider that this chapter provides a form of grounding for further discussion to debate over the point that ICT of the new wave of computing has disruptive, substantive, and synergetic implications, particularly on forms of urban planning and development that are necessary for urban sustainability practices in the future. This chapter also presents a basis for encouraging in-depth investigations on smart sustainable cities in the context of big data analytics and context-aware computing. All in all, despite the fear over the potential pitfalls these technologies can bring, they are widely believed and predicted to bring benefits that outweigh such pitfalls, thereby the need for stimulating innovation in this direction.

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Chapter 10
Transitioning from Smart Cities to Smarter Cities: The Future Potential of ICT of Pervasive Computing for Advancing Environmental Sustainability

Abstract Smart cities are evolving and ever changing, i.e., morphing into new faces. This is being fueled by the rapid computerization and urbanization of the world, driven by the evolvement of ICT visions of various forms of pervasive computing into deployable and achievable computing paradigms, as well as by the perceived role of advanced ICT in overcoming the challenge of urbanization. Indeed, visions of noteworthy advances in computing and ICT bring with them wide-ranging common visions on how cities as social fabrics will evolve in the future along with the immense opportunities and potential threats such future will bring. However, there are several critical issues that remain largely ignored concerning smarter cities. In particular, smarter (and smart) cities involve several problems—when it comes to their development and implementation as to their concrete contribution to and explicit incorporation of the fundamental goal of environmentally sustainable development. They moreover pose many risks to environmental sustainability due to the ubiquity of computing and the massive use of ICT throughout all urban domains. Also, relatively little or no attention has been given to smarter cities as future visions of smart cities in terms of the potential of ICT of various forms of pervasive computing to respond to the challenge of environmental sustainability. In addition, it is important not to conceive of smarter cities as "isolated islands", like some urban scholars might presume. Instead, the interplay between such cities and other scales, as well as the links to political and regulatory processes on a macro level have to be recognized. The purpose of this chapter is manifold. First, it reviews the key deficiencies, misunderstandings, fallacies, and challenges associated with smart and smarter cities with respect to environmental sustainability. Second, it identifies the significant risks that smarter cities pose to environmental sustainability, which are expected to escalate during the transition of smart cities to smarter cities. Third, it substantiates the potential that smarter cities hold in accelerating and advancing environmental sustainability on the basis of ICT of various forms of pervasive computing. The underlying assumption is that smarter cities are still at the early stage of their development and thus could, if planned strategically, do a lot more in this regard, including the mitigation of environmental risks posed by ICT itself, if linked to the goal of

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environmentally sustainable development. Fourth, this chapter endeavors to reflect on what it means for smart cities to move behind their foundational visions as they transition to smarter cities and embrace environmental sustainability as an important trend increasingly gaining prominence in urban development as a result of the unprecedented urbanization of the world. Fifth, this chapter probes both the ways in which the transition of smart cities to smarter cities (with environmental sustainability in mind) can be managed or governed at the macro level as well as the role of politics and policy in the creation and evolution of smarter cities. This entails drawing on different theoretical perspectives from socio-technical studies, innovation studies, and discursive studies, most notably transition governance; technological and national innovation systems; and the link between political practice and the emergence, insertion, and functioning of new discourses.

Keywords Smart cities · Smarter cities · Environmental sustainability
Environmentally sustainable development · Environmental risks
Visions · ICT · Pervasive computing · Big data analytics · Context-aware computing · Transition governance · Innovation systems · Socio-technical systems

10.1 Introduction

The evolving domination of the city due to the rapid urbanization of the world's population, coupled with the ubiquity of urban computing and the massive use of urban ICT, has become part of the mainstream debate on environmental urban sustainability. This unprecedented urbanization implies significant challenges for city governments associated with environmental sustainability due to the issues engendered by urban growth in terms of intensive energy consumption, endemic congestion, saturated transport networks, air and water pollution, toxic waste disposal, resource depletion, inefficient management of urban infrastructures and facilities, and so on (Bibri and Krogstie 2017a), despite urbanization epitomizing an emblem of social evolution. In short, the multidimensional effects of environmental unsustainability are set to worsen with urbanization. To disentangle these intractable problems requires evidently unprecedented shifts in urban thinking and planning—i.e., newfangled ways founded on more innovative and effective solutions and approaches with respect to how cities function and can be managed and developed (Bibri and Krogstie 2017a). This is crucial to rise to the substantial challenges arising from the rapid urbanization (in the event of continuous unsustainability) of the world. Besides, the planning of cities as complex systems and dynamically changing environments in terms of how they function and can be managed and developed requires innovative solutions as well as advanced approaches into understanding them.

Against the backdrop of the unprecedented urbanization, alternative ways of thinking about, conceiving of, and planning cities based on advanced ICT are materializing as to how cities can transition toward the needed environmental sustainability. This can be attained through adopting a set of integrated frameworks, procedures, processes, strategies, and policies to foster advancement and innovation in urban systems, namely built environment, infrastructure, administration, and ecosystem and human service provisioning, while continuously optimizing environmental efficiency gains. An increasing urgency to find and adopt smart solutions is driven by the rapid urban growth in terms of seeking out ways to address and overcome the associated challenges and ensuing effects pertaining to environmental sustainability (Bibri and Krogstie 2017a; Nam and Pardo 2011). Townsend (2013) portrays ICT development and urban growth as a form of symbiosis. This entails an interaction that is of advantage to, or a mutually beneficial relationship between, ICT and urban growth (Bibri and Krogstie 2017a). One way of looking at this is that urban growth can open entirely new windows of opportunity for cities to act as vibrant hubs of technological innovation in the context of environmental sustainability, which can be driven by and focused on solving the challenges arising from urbanization in the path to meet the goal of environmental sustainability. Indeed, a large number and variety of new technologies and applications are being developed and applied in response to the urgent need for dealing with the complexity of the knowledge necessary for addressing and overcoming the challenges of urbanization and sustainability in terms of novel and powerful decision-making systems and urban intelligence functions for operating, managing, and planning urban systems, as well as for coordinating and integrating urban domains. In all, there is an urgent need for developing and applying innovative solutions and sophisticated methods to overcome the environmental challenges of urbanization (United Nations 2016) and sustainability (Batty et al. 2012; Bibri and Krogstie 2017a, b). In particular, the big data and context-aware computing paradigm that is driving the transition from smart cities to smarter cities is in a penetrative path toward safely fueling unhindered progress on many scales and hence paving the way for accelerating and advancing environmental sustainability. Failing to exploit and harness the disruptive power of advanced ICT with respect to environmental sustainability in an increasingly technologized, computerized, and urbanized world and what this entails in terms of the extraordinary pressures on the environment means that the battle for environmental sustainability will be lost in the world's major cities.

Based on the above reasoning, new emerging faces of cities, which are characterized by deep embeddedness and pervasiveness of ICT and thus the infiltration of computer and information intelligence into the very fabric of urban systems and processes hold unparalleled potential, or are extremely well placed, to accelerate and advance environmental sustainability—if driven and guided by the agenda of sustainable development. Besides, it is high time for smart cities to get smarter beyond the technical advancement of ICT and the efficiency of smart solutions, and start focusing their efforts toward becoming well suited to the needs of the contemporary agendas of ICT of various forms of pervasive computing as regards to the advancement of environmental sustainability under what is labeled "smarter cities." This is predicated on the assumption that ICT of pervasive computing offers fascinating possibilities for monitoring, understanding, probing, assessing, and planning cities to improve and maintain their contribution to the goal of environmentally sustainable development (Bibri and Krogstie 2016a, 2017a, b). In other words, as ICT will become part of every urban operation, function, service, strategy, practice, and policy in smarter cities, i.e., everything to which it can be applied, it will be in a better position to instigate major urban transformations. This entails shaping how things can be created, done, and revolutionized in connection with the way urban systems and domains interrelate, coordinate, and collaborate in ways that support and can be aligned with the goal of environmental sustainability. Therefore, there is an increasing recognition that ICT of pervasive computing constitutes a promising response to the challenge of environmental sustainability of our time (Bibri and Krogstie 2016a, 2017a, b). This is anchored in the underlying premise that emerging and future ICT is extremely well positioned by the blend of data science, computer science, and complexity sciences upon which it is founded to build smarter cities capable of addressing intractable problems and complex challenges related to the environment. Especially, urban sustainability deals with the complex mechanisms and behavioral patterns involved in the profound interactions between social, environmental, physical, and engineered systems pertaining to cities to understand the underlying reciprocal relationships and changing dynamics, and to contribute to developing (rather upstream) solutions for tackling the complex challenges associated with the systematic degradation of such systems and the concomitant perils to natural environment and human well-being. To put it differently, the environmental gains and opportunities for the development of smarter cities on the basis of ICT of various forms of pervasive computing at every spatial scale will be enormous, especially when new digital technologies can be put in place that will integrate the countless sensor, actuators, and information processing systems that are fast proliferating across the domains of smart cities. In all, future ICT can well be leveraged in accelerating and advancing environmental urban sustainability (e.g., Batty et al. 2012; Bibri and Krogstie 2016a, 2017a, b; Kramers et al. 2014; Shahrokni et al. 2015). And emerging ICT has already made it possible to approach a range of issues around environmental sustainability in cities from a whole new perspective (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Batty 2013; Bibri and Krogstie 2017b). Therefore, ICT is increasingly seen to hold the key to an environmentally sustainable world, and this will be most clearly demonstrated in smarter cities of the future. In fact, smart cities getting smarter lies in finding and devising innovative ways of maintaining their contribution to the goal of environmentally sustainable development. There is an increasing consensus that smarter cities, if planned strategically and directed astutely, would represent the crucible for technological innovations supportive of environmental sustainability, as well as the best place where progress can be made with the application, diffusion, and adoption of such innovations.

Smarter cities typically rely on the fulfillment of the prevalent ICT visions of pervasive computing, most notably UbiComp, AmI, the IoT, and SenComp (Bibri and Krogstie 2017a, b). Recent discoveries in computing and advances in ICT applications have given rise to such socially disruptive technologies or inspiring technological visions. With their underlying technological advances, smarter cities are increasingly permeating urban debates and becoming interwoven with urban policy and politics with respect to strengthening the role of ICT in accelerating and advancing environmental sustainability (Bibri and Krogstie 2016a, 2017a). This is manifested in the rise of new faces of cities—namely ambient cities (e.g., Böhlen and Frei 2009; Thrift 2014), ubiquitous cities (Lee et al. 2008; Shin 2009), sentient cities (Shepard 2011; Grang and Graham 2007) and cities as Internet-of-everything (Kyriazis et al. 2014), as well as their increasing orientation toward environmentally sustainable development through smart initiatives and projects within technologically and ecologically advanced societies alike. This is anchored in the underlying assumption that as ICT becomes omnipresent, i.e., data sensing, information processing, and wireless networking technologies permeate urban infrastructures, facilities, designs, energy resources, ecosystem services, and citizens' objects, we can speak of cities getting smarter as to addressing complex environmental challenges and problems (Bibri and Krogstie 2016a, 2017a, b).

However, there has recently been a shift in cities striving for smart targets instead of (environmental) sustainability goals (Ahvenniemi et al. 2017; Bibri and Krogstie 2017a; Marsal-Llacuna et al. 2015). In more detail, despite the recent increase of research on smart and smarter cities—i.e., as a result of the evolvement of ICT visions into achievable and deployable computing paradigms, pushed by big data analytics and context-aware computing—the bulk of work has tended to deal largely with the advancement of ICT of various forms of pervasive computing and its potential only in terms of novel applications and services and their role in improving the quality of life of citizens and enhancing economic productivity and efficiency in the realm of smart cities. Therefore, there are important questions that are barely explored to date or largely ignored concerning the untapped potential of emerging and future ICT in accelerating and advancing environmental sustainability, especially in the context of smarter cities. Accordingly, both existing smart cities and emerging smarter cities raise several issues—when it comes to their development and implementation as to their concrete contribution to and explicit incorporation of the fundamental goal of environmentally sustainable development (Bibri and Krogstie 2017a). These issues entail deficiencies, misunderstandings, and fallacies (e.g., Bibri and Krogstie 2016a, 2017a; Colldahl, Frey and Kelemen 2013; Greenfield 2013; Höjer and Wangel 2015; Kramers et al.2014). Moreover, from a conceptually different angle, smart and smarter cities pose many risks to environmental sustainability (e.g., Bibri and Krogstie 2016a, 2017a; Greenfield 2013) due to the ubiquity of computing and the massive use of ICT throughout all urban domains. Driving this line of research are questions involving the way smart and smarter cities should measure and identify risks, uncertainties, and hazards associated with the use of ICT, as well as why and when it is important to set safety standards, e.g., in relation to the environment (Bibri and Krogstie 2016a, 2017a). Indeed, the most imminent threat of ICT in the context of such cities lies in its multidimensional effects on the environment (e.g., Bibri and Krogstie 2016a). In addition, it is important not to conceive of smarter cities as "isolated islands", like some urban scholars might presume. Instead, the interplay between such cities and other scales, as well as the links to political and regulatory processes on a macro level, have to be recognized. Macro processes of political regulation and policy is determining in the discursive-material dialectics of smarter cities as a techno-urban transformation.

Consequently, the need to explicitly incorporate environmental sustainability in smart and smarter cities has become a key research direction and new wave of urban thinking in recent years (see, e.g., Ahvenniemi et al. 2017; Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a; Höjer and Wangel 2015; Kramers et al. 2014; Nam and Pardo 2011; Neirotti et al. 2014). This has come to the fore after the realization that advanced technologies have been, and continue to be, used in existing smart and emerging smarter cities without making any contribution to environmental sustainability (Bibri and Krogstie 2017a). In addition, although several studies have been conducted in recent years addressing the role of smart cities in improving environmental sustainability (e.g., Ahvenniemi et al. 2017; Al Nuaimi et al. 2015; Bibri and Krogstie 2017a), relatively little or no attention has been given to smarter cities as future visions of smart cities in terms of the potential of the underlying ICT of various forms of pervasive computing to respond to the challenge of environmental sustainability. Most topical studies tend to only pass reference to the role that future ICT could play in addressing environmental challenges. Yet, there is increasing evidence that significant opportunities are involved, and that the contribution of smarter cities to the goal of environmentally sustainable development is still untapped and under-researched (e.g., Bibri and Krogstie 2017a, b). However, smarter cities pose special conundrums and significant challenges that should be addressed and overcome to be able to realize their full potential for accelerating and advancing environmental sustainability, to reiterate.

Our endeavor is in the spirit of why and how smart cities should emphasize the importance of explicitly incorporating the goal of environmentally sustainable development as well as engage into concrete efforts to mitigate the risks posed by ICT to environmental sustainability in the process of transitioning to smarter cities. This topic has become a mainstream theme in the debate on ICT innovation and sustainability in the context of smart cities of the future (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017b).

The purpose of this chapter is manifold. First, it reviews the key deficiencies, misunderstandings, fallacies, and challenges associated with smart cities and smarter cities with respect to environmental sustainability. Second, it identifies the significant risks that smarter cities pose to environmental sustainability, which are expected to escalate during the transition of smart cities to smarter cities. Especially, the dominant ICT visions of pervasive computing are rapidly evolving into deployable and achievable computing paradigms, thereby paving the way for smarter cities to rise and propagate. In this spirit, this chapter as to its third aim substantiates the potential that smarter cities hold in accelerating and advancing environmental sustainability on the basis of ICT of various forms of pervasive computing. The underlying assumption is that smarter cities are still at the early stage of their development and thus could, if planned strategically, do a lot more in this regard, including the mitigation of environmental risks posed by ICT itself (GHG emissions, intensive energy consumption, toxic waste, resource depletion, etc.), if linked to the goal of environmentally sustainable development. This could occur as they evolve and become technologically mature, and optimistically, before they get widely adopted and deployed in the years ahead. Fourth, this chapter endeavors to reflect on what it means for smart cities to move behind their foundational visions as they transition to smarter cities and embrace environmental sustainability as an important trend increasingly gaining prominence in urban development as a result of the unprecedented and rapid urbanization of the world. Fifth, this chapter probes both the ways in which the transition of smart cities to smarter cities (with environmental sustainability in mind) can be managed or governed at the macro level as well as the role of politics and policy in the creation and evolution of smarter cities. This entails drawing on different theoretical perspectives from socio-technical studies, innovation studies, and discursive studies, most notably transition governance; technological and national innovation systems; and the link between political practice and the emergence, insertion, and functioning of new discourses.

The motivation for this endeavor is fourfold. First, smarter cities are evolving into a realist scholarly enterprise and thus gaining momentum as an urban and academic pursuit in technologically and ecologically advanced nations. Second, it is of relevance and urgency to invigorate the application demand for the smarter solutions for environmental sustainability that ICT of various forms of pervasive computing can offer in the context of smarter cities. Third, it is of importance to highlight the untapped potential such cities hold in this regard in order to stimulate new research opportunities and direct new technological innovations in support of environmental sustainability. Fourth, it is timely to take stock of what has been learned and accumulated as substantive knowledge on how ICT of various forms of computing could contribute to environmental sustainability and mitigate environment risks it poses. This endeavor is intended to create an integrated research field and to apply the underlying interdisciplinary research more effectively, with the aim of tackling the unsolved and pressing issues related to current smart cities with respect to the limited extent of their contribution to the goal of environmentally sustainable development.

The remainder of this chapter is structured as follows. Section 10.2 provides an overview of the field of smart and smarter cities in terms of its state-of-the art research and development, shortcomings, and challenges. In Sect. 10.3, we provide a detailed account of environmental risks posed by ICT of various forms of pervasive computing, covering direct, indirect, systemic, rebound, and constitutive effects, as well as propose different approaches into mitigating such risks and thus dealing with such effects. Key philosophical and disciplinary debates on smarter cities are addressed in Sect. 10.4. Section 10.5 discusses the productive and constitutive force of ICT of various forms of pervasive computing, and documents the potential that smarter cities hold in accelerating and advancing environmental sustainability on the basis of big data analytics and context-aware computing as a set of advanced technologies and their novel applications. In Sect. 10.6, we reflect on what it means for smart cities to move behind their foundational visions as they transition to smarter cities and embrace environmental sustainability as an important trend increasingly gaining prominence in urban development in an increasingly urbanized world. In Sect. 10.7, we delve into the governance of the transition from smart cities to smarter cities, focusing on the key premises of transition governance approach, multi-actor or scale governance, power relations, socio-technical landscape, socio-technical regimes, and innovative technological niches, as well as how these are intricately interrelated. Section 10.8 elucidates and discusses the shaping role of political action in the emergence, insertion, and functioning of smarter cities as a techno-urban discourse and an amalgam of innovation systems. The chapter ends; in Sect. 10.9, with concluding remarks and some thoughts.

10.2 A State-of-the-Art Overview

10.2.1 Smart Cities

10.2.1.1 Deficiencies, Misunderstandings, and Challenges Pertaining to Environmental Sustainability

It is important to point out that the outcome of this detailed overview is based on a recent interdisciplinary literature review carried out by Bibri and Krogstie (2017a). The topic of smart cities brings together a large number of previous studies, including research directed at conceptual, analytical, and overarching levels, as well as research on specific technologies and their potentials and opportunities. Indeed, recent years have witnessed a great interest in and a proliferation of academic publications on the topic of smart cities. This reflects the magnitude and diversity of research within the field. The existing body of research is further rapidly burgeoning, where the emphases and aims tend to be varied, as manifested in researchers' miscellaneous contributions to the conceptualization, design, development, and implementation of smart cities. From a general perspective, the field of smart cities merges broad streams of scholarship, which entail various strands of research. One strand of research is concerned with the theory and practice of urban computing, applied urban science, and urban ICT. This line of work addresses questions pertaining to urban sensing, urban informatics, big data analytics, context-aware computing, cloud computing infrastructures, data processing platforms, urban simulation models, urban intelligence functions, database integration, wireless technologies and networks, decision support systems, and so on. These varied technologies are applied to diverse urban domains. This strand of research focuses mainly on technological advancement, use, and application for efficiency and management purposes, which tend to prevail in the field of smart cities compared to environmental aspects. This chapter is concerned with the untapped potential of emerging and future ICT in advancing environmental sustainability in the context of smarter cities as future visions of smart cities. However, remaining on the same strand of research, a large body of conceptual work on smart cities has attempted to develop theoretical perspectives and models to provide a basis for further discussions on what such urban development approach aspires to deliver as to different aspects of smartness, though with less emphasis on environmental sustainability. Adding to this academic endeavor is a large body of analytical work which has endeavored to investigate numerous propositions—in the light of emerging and future ICT—about what makes a new city badge or an existing city regenerate itself as smart, why a city uses ICT to develop new urban intelligence functions, and how a city develops urban services using modern ICT, among other things. In all, much of early research work has tended to conceptualize, describe, classify, or rank the phenomenon of smart city based on the use of modern ICT in relation to a wide variety of urban operations, functions, designs, and services. Whereas recent research has typically focused on analyzing different projects, prospects, and initiatives and their possible urban impacts, with an emphasis on specific technologies and their applications, such as big data analytics, urban informatics, context-aware computing, and cloud computing, along with the challenges involved in achieving various smart city statuses. It is worth noting that, as the extensive interdisciplinary literature carried out by Bibri and Krogstie (2017a) shows, there is a great deal of diversity among smart cities, and in this sense, it is pertinent to view the smart city as an ambition which can be for varied objectives and shaped by diverse disruptive technologies, and which there will be multiple ways to achieve. Of importance to underscore in this regard is that the so-called advanced ICT is sometimes used without making any contribution to environmental sustainability.

Another strand of research looks at the impacts ICT has on how we think about and conceive of cities in the sense of propelling us to rethink or alter some of the core concepts through which we analyze, operate, organize, assess, plan, and value urban life toward creating more sustainable ways of dwelling in and interacting with urban environments (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Shepard 2011; Solanas 2014). A key line of work within this strand tends to focus on integration proposals from a more conceptual perspective. The underlying idea is that some aspects of smart city approaches can be combined with some facets of sustainable city models (e.g., Al-Nasrawi et al. 2015; Höjer and Wangel 2015; Kramers et al. 2014), or the other way around. In the latter case, the aim evolves around enhancing the contribution of sustainable cities to sustainability with support of advanced ICT (e.g., Bibri and Krogstie 2017b). This is anchored in the underlying assumption that ICT is founded on the application of data science, computer science, and complexity sciences, which are well suited to addressing the complex challenges and problems of environmental sustainability in particular. This tends, though, to involve mostly the infrastructural, operational, and functional aspects of sustainable cities, rather than the physical and spatial facets in terms of integrating them with advanced technologies for better understanding, analyzing, evaluating, and planning purposes. Indeed, any kind of integration involving smart ICT and sustainable development requires a holistic approach into enabling cities to realize their potential as to their contribution to environmental sustainability in a concrete sense. In this regard, cities that stand on a spectrum of the sustainability scale can embrace and exploit smart development initiatives. By the same token, cities that stand on a spectrum of the smartness scale can embrace and exploit sustainable development initiatives. In this line of thinking, recent research endeavors (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Ahvenniemi et al. 2017) have started to focus on how to enhance smart city approaches in an attempt to achieve the required level of environmental sustainability with respect to urban operations, functions, services, and designs. The best cities are those that support the generation of creative ideas and, more importantly, promote sustained development (Jacobs 1961). Besides, for existing smart cities to thrive, they need to leverage their informational landscape in ways that enable them to incorporate and sustain their contribution to environmental sustainability. This is what we aim to emphasize, especially in relation to their transition to smarter cities. In all, the main premise underlying the recently suggested integration proposals is to highlight that smart cities hold great potential to advance environmental sustainability—if ICT advancement, use, and application can be directed for this goal. As smartness targets and sustainability goals are interconnected, and thus smart and smarter cities can still share similar goals as sustainable cities (e.g., Ahvenniemi et al. 2017; Bibri and Krogstie 2017a), it is important to understand the link between the concepts of smart city and sustainable city (Bifulco et al. 2016). This relates to the ongoing debate over diverse technologies playing an instrumental role in achieving environmental sustainability, as well as over the so-called smart technologies being used without supporting environmental sustainability in smart cities (Bibri and Krogstie 2017a; Höjer and Wangel 2015).

Another wave of research, which relates to the above one, focuses on the current deficiencies or inadequacies associated with the sustainability of smart cities. The main issue being addressed and discussed is that not all the definitions of smart city incorporate the goal of environmentally sustainable development. According to Höjer and Wangel (2015), the existing concepts of smart city set up no baseline for sustainability, nor do they define what sustainable development is, although defining this concept is crucial to know the purposes for which smart ICT should be used, as well as to assess whether (or the extent to which) smart ICT contributes to the goals of sustainable development or delivers the desired outcomes in this regard, especially in relation to the environmental dimension of sustainability. As echoed by Kramers et al. (2014), the concept of smart city says little about how any substance behind the smart solutions links to sustainability, and particularly has little to do with environmental concerns or solutions. In line with this thinking, in studying the concept of smart city through a lens of strategic sustainability, Colldahl et al. (2013) argue that while the concept of smart city is a powerful approach into enabling cities to become sustainable due to its potential to address some sustainability challenges by improving efficiency in urban systems, in addition to having an innovative and forward–thinking approach to urban planning, it is currently associated with shortcomings with regard to sustainability, i.e., it "does not necessarily allow for cities to develop in a sustainable manner." There are various approaches that can be espoused to mitigate these shortcomings so that smart cities can evolve toward sustainability in a more effective way—as they transition to smarter cities. One of which is to endeavor to explicitly incorporate the goal of environmentally sustainable development in the concept of smart city and to work toward developing smart cities in ways that direct ICT development and innovation toward primarily increasing their contribution to such goals. Especially, topical studies have highlighted the need for smart cities to pursue this path, and have also called for caution when encountering current smart city initiatives. In a very recent study, Ahvenniemi et al. (2017) used 16 existing smart city and sustainable city assessment frameworks (eight related to sustainable city and eight related to smart city) to examine how smart cities compare with sustainable cities as to both commonalities and differences. They compare these frameworks as performance measurement systems with respect to 12 application domains (namely natural environment; built environment; water and waste management; transport; energy; economy; education, culture, science, and innovation; well-being; health and safety; governance and citizen engagement; and ICT) and three impact categories (environmental, economic, and social sustainability) involving 958 indicators altogether. The authors observe a much stronger focus on modern ICT and what it entails in terms of smartness in the smart city frameworks as to social and economic indicators, but a lack of environmental indicators. They conclude that smart cities need to improve their sustainability with support of advanced ICT, and suggest on the basis of the gap between smart city and sustainable city frameworks further development of smart city frameworks and redefinition of the concept of smart city. Accordingly, they advocate that the assessment of smart city performance should use impact indicators that measure the contribution of smart cities to environmental sustainability and thus to the environmental goals of sustainable development, among other things. Kramers et al. (2014) suggest that the concept of smart sustainable city can be used as a way of emphasizing initiatives where smartness is directed toward promoting environmental sustainability. As supported by Höjer and Wangel (2015), smart cities become sustainable when ICT is employed for improving sustainability. These prospects are most likely to become clear in smarter cities as future visions of smart cities.

In addition, given the fact that sustainability is an integral part of some definitions of smart city (e.g., Bibri and Krogstie 2017a), the concept of smart city has been used interchangeably with that of smart sustainable city, leading to confusion and misunderstanding in the urban domain. Some views might contend that “the smart city is the smart sustainable city and that the word ‘sustainable’ can be left out without further ado” (Höjer and Wangel 2015, p. 9). The different conclusions led to by recent studies (e.g., Kramers et al. 2013; Neirotti et al. 2014) on the integration of sustainability in smart cities can be explained by the gap between the theory and practice of smart cities. In contrast to the study carried out by Kramers et al. (2013), which shows that a few concepts of smart city include explicit objectives of environmental sustainability, the study conducted by Neirotti et al. (2014) indicates that environmental sustainability is explicit through the most common types of urban application domains, namely “Natural Resources and Energy” and “Transportation and Mobility” for smart city initiatives. Nevertheless, the key insight here is that the concept of smart city and what it entails in terms of smart applications hold some potential for sustainability—if astutely leveraged in the needed transition toward sustainable urban development. In other words, the concept of smart city provides solutions and approaches that can make cities sustainable in a smart way—if driven by a long-term planning approach that centers on sustainability. Colldahl et al. (2013) argue that the concept of smart city is a powerful approach to enabling cities to move toward sustainability.

Much of the aforementioned literature (Bibri and Krogstie 2017a) on smart cities focus on specific technologies and their potentials and opportunities. The state of research in the realm of smart cities—a burgeoning scholarly interdisciplinary field and science-based, techno-urban enterprise—shows varied focuses of topical studies as to the potential of new technologies and their novel applications and services. This entails bringing advanced solutions for diverse complex problems related to such urban domains, as well as providing a plethora of new online and mobile services to citizens to improve the quality of their life with respect to education, health care, safety, well-being, accessibility, participation, and so forth. However, while ICT progress in this regard is rapid and manifold, it seems to happen ad hoc in the context of smart cities when new technologies and their applications become available, rather than grounded in a theoretically and practically focused overall approach—e.g., the most needed and urgent solutions that ICT can offer in the context of environmental sustainability as an overarching urban application domain. In addition, to develop smart solutions of less relevance to environmental concerns is not the most effective way of driving ICT development and innovation in the context of smart cities. What is alternatively needed, or rather what smart solutions ought to be created for, is a realistic tackle of the most pressing problems (e.g., energy inefficiency, environmental degradation, pollution, toxic waste disposal, etc.). As to energy efficiency, for instance, Kramers et al. (2014) argue that the available opportunities need to be explored thoroughly and investigated as to how they can best support the implementation of ICT solutions to turn the potentials into real energy savings, and concurrently ICT industry needs to learn how best to design and implement the so-called smart solutions that lower energy usage. However, at this stage, there is much focus on technical dimensions as to ICT development and innovation, which pertains to all existing smart city (and emerging smarter city) approaches. Therefore, it is high time to link technological progress with the agenda of environmentally sustainable development and thus to justify future ICT investments by environmental concerns in the context of smarter cities.

While the literature shows a diversity of smart city frameworks, the one developed by Giffinger et al. (2007): the European Smart Cities Ranking, remains the most widely quoted, used, and applied in the field. It has been developed to enable the comparison of cities and to assess their development toward the needed smartness. Accordingly, it has been used as a classification system—based on six distinct dimensions, namely smart mobility, smart environment, smart living, smart people, smart economy, and smart governance—against which smart cities can be gauged. Each dimension comes with a set of factors or criteria that evaluate success under that dimension. In this regard, a city identifies, based on the examination of the current state of its development, the areas that might necessitate further improvements, and then attempt to meet the necessary conditions so as to be able to badge or regenerate itself as smart. In doing so, it can set goals based on its unique circumstances by pursuing the six dimensions in terms of related visions or prospects (Giffinger et al. 2007; Steinert et al. 2011). However, this model does neither provide a prioritization of these dimensions as to their contribution to environmental sustainability, nor does it specify how they can add to urban planning and development practice in terms of environmental sustainability (Bibri and Krogstie 2017a, b). Nevertheless, this connotation of smart city is seen as a strategic devise to highlight the growing role and potential of ICT in enabling and catalyzing sustainable urban development processes. Other smart city frameworks (e.g., Chourabi et al. 2012; Correia and Wuenstel 2011; Neirotti et al. 2014) tend to differ slightly from the aforementioned one by combining, rearranging, extending, or renaming the defining characteristics or constituting features (i.e., application domains) of smart cities.

Another set of frameworks has been developed for certain urban domains. In this regard, some frameworks have been proposed to benchmark cities and to assess the smartness of their transportation systems, urban mobility, the environment, or the quality of life (Bibri and Krogstie 2017a). In relation to environmental sustainability, Ahvenniemi et al. (2017, p. 235) state, quoting, Marsal-Llacuna et al. (2015), "the smart city assessment builds on the previous experiences of measuring environmentally friendly and livable cities, embracing the concepts of sustainability and the quality of life but with the important and significant addition of technological and informational components." A study conducted by Bifulco et al. (2016) addresses the connections between the technologies enabling the smart city characteristics as conceptualized in the framework proposed by Giffinger et al. (2007) and the goal of environmental sustainability. While the authors outline a new research avenue for the development of frameworks that amalgamate ICT with environmental sustainability in, and new indicators for the evaluation of, smart interventions, no details are provided as to how to develop such frameworks in terms of the technological and urban components needed to achieve the purpose.

10.2.1.2 Scientific Challenges and Environmental Risks

There are numerous challenges facing smart cities. The focus is on the most relevant ones in the context of this chapter. Batty et al. (2012, pp. 481–482) identify several scientific challenges, namely:

To relate the infrastructure of smart cities to their operational functioning and planning through management, control, and optimization;
To explore the notion of the city as a laboratory for innovation;
To provide portfolios of urban simulation which inform future designs;
To develop technologies that realize a better quality of city life; and
To develop technologies that ensure informed participation and greater and more effective mobility.

Furthermore, a large part of research work on smart cities is currently focusing on a wide variety of technological propositions about what makes cities smart in terms of environmental sustainability. However, this relationship is too often, if not always, addressed separately from the rather established strategies through which sustainable cities can be achieved, namely density, diversity, compactness, mixed land use, sustainable transport, ecological design, and passive solar design. For many contemporary urban scholars, theorists, and planners, these strategies are necessary to be adopted to achieve sustainability (see, e.g., Dumreicher et al. 2000; Williams et al. 2000; Jabareen 2006; Kärrholm 2011)—irrespective of how intelligently other urban systems than the built form can be operated, managed, planned, and developed (Bibri and Krogstie 2017b). ICT as an enabling and constitutive technology can indeed make substantial contributions in relation to these strategies. Cities become smartly sustainable when smart ICT is employed for making them more sustainable (Höjer and Wangel 2015), to iterate. How and when this can, or should, be accomplished and done is a question of what the body of research on both sustainable cities and smart cities (Bibri and Krogstie 2017a) suggests as to what is currently of high priority, urgency, timeliness, and necessity to pursue as research endeavors in order to address the most critical issues around existing sustainable cities (e.g., the evaluation of the extent to which sustainable cities contribute to the goal of environmentally sustainable development the better translation of environmental sustainability into the built and infrastructural forms of sustainable cities) using innovative solutions being offered by smart city approaches (Bibri and Krogstie 2017b). Another way forward is simply to adopt the cutting-edge solutions being offered by smarter cities in terms of the underlying core enabling technologies and their novel applications and services (big data analytics and context-aware computing) associated with the advancement of environmental sustainability (Bibri and Krogstie 2016a, 2017a, b). It is argued that as data sensing, information processing, computational and data analytics capabilities, and wireless communication solutions become deeply embedded into urban systems and domains to address the challenge of environmental sustainability, we can speak of cities getting smarter as to contributing to the goal of environmentally sustainable development more effectively and efficiently (Bibri and Krogstie 2016a, 2017a, b). However, irrespective of the type of smarter solutions being proposed for environmental sustainability, it is of critical importance to ensure smart initiatives resonate with the significant themes in debates on the typologies and design concepts of sustainable urban forms (see Chap. 7 for a relevant thematic analysis). Bibri and Krogstie (2017b) propose a matrix linking these themes with the applications being offered by ICT of various forms of pervasive computing in the context of smart sustainable cities of the future.

Smart cities pose many risks to environmental sustainability (e.g., Bibri and Krogstie 2016a; Greenfield 2013) due to the ubiquity of computing and the massive use of ICT across urban systems and domains. Driving this line of research are questions involving the way smart cities should measure and identify risks, uncertainties, and hazards associated with the use of ICT, as well as set safety standards. This pertains particularly to environmental sustainability. Indeed, the most threat of ICT in the context of smart cities lies in its multidimensional effects on the environment (e.g., Bibri and Krogstie 2016a). The real challenge lies in estimating the potential for curbing energy usage in a meaningful way in the sense of mitigating concomitant environmental impacts. The underlying assumption is that ICT as an enabling and constitutive technology is embedded into a much wider socio-technical landscape (economy, institutions, policy, politics, and social values) in which a range of factors and actors other than techno-scientific ones are involved (Bibri and Krogstie 2016a). Therefore, "without careful implementation in combination with other measures, ICT solutions might also result in increased energy use instead of a reduction, either directly or in other parts of the energy system… [I] n order to establish the full impact of implemented ICT solutions, it is important to take into account all direct and indirect changes resulting from this, including the impact from the ICT solution's entire life cycle. This also points to the importance of combining its implementation with policy and planning instruments, so as to ensure that the efficiency gains actually lead to a reduced use of energy." (Kramers et al. 2014, p. 60)

10.2.2 Smarter Cities

10.2.2.1 Materialization and Characterization

In modern, high-tech society, of the world's major cities, some are becoming smart in a more or less self-conscious or gradual way, and others are already regarded as smart and manifestly planning to become smarter—especially in technologically (and even ecologically) advanced nations. Regardless of the path being pursued by these cities toward becoming smart or smarter, they will all evolve into becoming fully computerized and thus technologized on a hard-to-imagine scale at varying degrees due to the rapid pace distinctively characterizing the development of ICT that is increasingly being boosted and fueled by scientific discoveries in computing and its quick-paced ubiquity and massive use in almost all urban domains to address the numerous complex challenges facing contemporary cities in the context of both sustainability and urbanization. The evolving smart cities into smarter cities are taking various forms, including the following:

New cities badging themselves as smart (e.g., carbon neutral, energy-efficient, wired at all levels);
Existing cities regenerating themselves as smart (the emergence of spontaneous developments of new ICT and its embeddedness in key urban domains);
Cities using ICT to develop new urban intelligence functions (advanced optimization strategies and powerful forms of simulation models for urban operations and functions);
Cities developing new urban services using modern ICT (wirelessly ad hoc and mobile networks, database networking and integration, and cloud computing);

Cities developing science parks and techno-poles focused on high technologies; and Cities developing online and mobile forms of governance and participation.

The rise of these cities is manifested in large-scale deployment and implementation of sensor technologies, cloud computing infrastructures, data/information processing platforms, middleware architectures, wireless communication networks, and innovation labs across urban environments. These constitute the core enabling technologies of ICT of various forms of computing. Indeed, the increasing convergence, prevalence, and advance of urban ICT, coupled with the proliferation of the underlying core enabling technologies, is giving rise to and producing new faces of cities that are quite different from what has been experienced hitherto on many scales. These cities are labeled "smarter cities" because of the magnitude of ICT and the profusion of data as to their embeddedness and use in urban systems and domains. They include ubiquitous cities (e.g., Batty et al. 2012; Lee et al. 2008; Shin 2009), ambient cities (e.g., Böhlen and Frei 2009; Crang and Graham 2007), sentient cities (e.g., Shepard 2011; Thrift 2014), and cities as Internet-of-everything (e.g., Kyriazis et al. 2014; Perera et al. 2014; Zanella et al. 2014). They are seen as future forms of smart cities. The initiatives of smarter cities enabled by ICT of various forms of pervasive computing in several countries across Europe, the USA, and Asia are increasingly considered as national urban development projects that center on strengthening the role of ICT, especially big data analytics and context-aware computing, in urban operations, functions, services, designs, strategies, and policies in terms of management, control, optimization, planning, development, and governance to advance environmental sustainability, among other things. This is clearly manifested in the ongoing large-scale deployments of UbiComp, AmI, the IoT, and SenComp taking place across the world's major cities to integrate and monitor existing infrastructures and facilities, to increase coordination and collaboration amongst different urban domains and hence urban actors, to provide more efficient services to citizens, to manage and plan urban activities, to optimize resources utilization, and to stimulate innovative business models. In view of that, across the globe, many cities are being planned to be wired, connected, networked, and transformed into a continuous stream of data that can be processed, analyzed, and modeled by large machines for a wide variety of decision-making and service delivery processes. Evidently, the interactive dynamics of change in urban technologies, institutions, and strategies are driving the initiatives of information society within several technologically and ecologically advanced nations as to the process of the design and development of smarter cities.

Discourses on smarter cities are relatively new; the terms describing smarter cities only entered the public mainstream between the late 2000s and the early 2010s. This well explains the related phase of research being in its early stage, so being the materialization of smarter cities. They are becoming rather more powerful and established, as contemporary urban scholars and planners relate to them in many contexts of urban practices, including environmentally sustainable development, yet not as of much focus as on ICT advancement and its potential for enhancing economic productivity and efficiency as well as the quality of life of citizens. This goes in fact in line with what the prevalent ICT visions postulate as to a paradigmatic shift in urban computing and society (see Bibri 2015b). Drastic urban transformations are expected to result from the implementation of ICT of various forms of pervasive computing (see, e.g., Böhlen and Frei 2009; ISTAG 2003; Kyriazis et al. 2014; Shepard 2011; Shin 2009; Thrift 2014). The core enabling technologies shared by ICT of various forms of computing are indeed instigating paradigm shifts in urban planning and development that are of an unprecedented kind. However, several sentient, ambient, ubiquitous, and the IoT applications, which are based on the conception of the city as a collection of infrastructures, platforms, applications, and services that are to be managed efficiently, are still under development (Bibri and Krogstie 2016a). Moreover, notwithstanding the positive development expected by these advanced technologies, there seem to be more challenges ahead to face than prospects to embrace. This relates to the deficiencies of emerging smarter city approaches in terms of lacking a holistic orientation as to integrating environmental concerns and socioeconomic needs with technological and economic opportunities. The quality of promoting environmental sustainability is also of inadequate nature. A perspective of balanced smarter urban development requires the following, to draw on Bibri and Krogstie (2016a):

Balancing aims and practices in support of environmental, social, and cultural sustainability with the traditional economic and technological biases;
Favoring ICT innovation endeavors linked to the most urgent societal challenges and to the untapped transformational effects of ICT as to the environmental and the quality of life; and
Formulating decisions based on a wide (and genuine) participation of all groups of citizens, especially in relation to environmental concerns.

Distinct institutional practices are, though, required that can support the balancing of these aims and practices and the approaches to these innovation and decision-making undertakings. Achieving smarter cities requires an all-encompassing understanding of urban complexities and interconnections between the social and environment components (see Nam and Pardo 2011). Therefore, it is important and invaluable to at this stage of development sensitize researchers, scholars, policymakers, and decision-makers in the field of urban planning and development to the fascinating possibilities that exist for ICT of various forms of pervasive computing in terms of accelerating and advancing environmental sustainability in the context of smarter cities. Important to note is that while such cities as advanced or future forms of smart cities are currently being practiced in ways that pretty much involve most of the environmental issues discussed above in relation to smart cities—the windows of opportunity are such wide that they could be reoriented into a more environmentally sustainable direction given that they are still in the early stage of their development. Regardless, the common claim made about future cities is that they will become sentient, ambient, ubiquitous, and Internet-of-everything, as they will be filled with ICT and resultant profusion of data clouds. Already, city development in this direction is, by all accounts, happening and increasingly stimulated by new advances in ICT of various forms of pervasive computing (e.g., Bibri and Krogstie 2016a).

10.2.2.2 Key Research Issues and Current Shortcomings

At this stage of research within the field of smarter cities, much of work tends to describe the phenomena, conceptualize the terms, discuss the assumptions and claims, and provide some normative prescriptions for achieving their statuses (e.g., Böhlen and Frei 2009; Kyriazis et al. 2014; Lee et al. 2008; Shepard 2011; Shin 2009; Thrift 2014). Another line of work focuses on highlighting the immense opportunities and fascinating possibilities provided by smarter cities as advanced forms of smart cities and the merits of the related ICT visions—i.e., the potential of socially disruptive technologies and their novel applications for bringing advanced solutions for solving a range of socioeconomic challenges and environmental problems, as well as for providing a plethora of innovative services to citizens to improve the quality of their life. However, the technical advancement of such technologies tends at this stage to dictate the path of their progress in the sense that, as with smart cities, this progress continues to happen ad hoc when new technologies and their applications and services become available—rather than grounded in a theoretically and practically focused overall approach—e.g., the most needed solutions that ICT of various forms of pervasive computing can offer in the context of environmental sustainability. In more detail, there is too much focus on the technical dimension of ICT development in smarter cities instead of directing it toward resolving the most pressing issues and complex challenges pertaining to environmental sustainability, notwithstanding the significant opportunities for emerging and future ICT in relation to advancing the urban model with regard to the environmental dimension of sustainability (Bibri and Krogstie 2017a, b). Furthermore, there has been no attempt thus far to develop any model of any class of smarter cities that can be used as a classification system against which such cities can be evaluated in terms of the way they intend to smarten up their contribution to environmental sustainability on the basis of ICT of various forms of pervasive computing they attempt to instantiate with respect to what UbiComp, AmI, the IoT, and SenComp claim or aspire to deliver as to the future form of smart sustainable urban development (e.g., Bibri and Krogstie 2017a). Therefore, it is high time to align ICT development in this direction with the goal of environmental sustainability, and thus to justify future ICT investments by environmental concerns in the context of smarter cities. Accordingly, what could be more pertinent and more meaningful for smarter cities as future forms of smart cities is to adopt clear strategic paths for ICT innovation and thus smart urban initiatives and projects toward tackling environmental issues by rising to the bigger challenges of the present, as well as to seek to make a positive and profound impact on the urban world over the long run, to use the terminology of Bibri (2015b). Working toward the visions of future smart cities raises the risk of neglecting the environmental challenges of the present. This relates to what is known as the proximate future, a future of smarter cities with high potential for advancing their contribution to the goal of environmentally sustainable development that is just around the corner but always postponed. Working for the proximate future allows everyone to take their favorite challenges and assume that all the limitations of the present associated with the environment will soon be solved by someone else. The obvious repercussion is that real environmental issues remain unsolved. In addition, this may often be used as the justification for the lack of delivery and realization of smarter cities when it comes to bringing value to the real environmental problems of today. Additionally, it is most invaluable for future ICT development in the context of smarter cities to be driven by the challenges of environmental sustainability, rather than by sheer technical developments, industrial leadership, and global competitiveness. This is the kind of strategic path of technological progress that should be embraced and pursued in the years ahead. Only then can smarter cities evolve into techno-urban innovations that can make urban living more environmentally sustainable. Conversely, having pre-configured or pre-formatted solutions for yet-to-find urban problems, or developing solutions which are of less relevance to environmental concerns, is definitely not the most effective way of driving ICT development and innovation in the context of smarter cities.

Furthermore, not long time ago, around the early 2010s, the literature on smarter cities (e.g., Böhlen and Frei 2009; Kyriazis et al. 2014; Shepard 2011; Shin 2009; Thrift 2014) started taking an analytical direction, testing various propositions about what makes a city smarter in terms of the extent to which data sensing, information processing, and wireless networks technologies can be embedded into urban systems and domains to enhance diverse aspects of urban living, as well as in terms of what drives the trend of being smarter as regards to carbon neutrality, energy-efficiency, wiring at all levels, urban intelligence functions, new online and mobile services, and so on. In this regard, smarter cities tend to pursue the path of smart cities by focusing on specific technologies, opportunities, and domains of application as dictated by what ICT has to offer based on the state of its development. In all, the state of research in the realm of smarter cities shows varied emphases of topical studies as to the immense opportunities and fascinating possibilities that can be provided by new socially disruptive technologies and their novel applications for bringing advanced solutions for solving many problems pertaining to various urban domains, as well as for providing a plethora of novel services to citizens to improve the quality of their life.

Here we present a tabulated version of the shortcomings of smarter cities (see Table 10.1), which are distilled based on a recent literature review carried out by Bibri and Krogstie (2017a) on the field of smart and smarter in terms of its state-of-the art research and development, among other things.

Table 10.1 Current shortcomings of smarter cities

Current shortcomings of smarter cities
A lack of a shared definition and a difficulty in identifying a common trend
Deficiencies in the explicit incorporation of the goal of environmentally sustainable development
A weak connection between the concepts of smarter cities and environmental sustainability
The concept saying little about whether there needs to be any substance behind the claim of being smarter or how that links to environmental sustainability
Discrepancies between technological innovations and environmental problems
Smart projects contingent upon available resources, financial capabilities, and urban politics and policy—rather than on a clearly focused approach into addressing the environmental challenges
Mismatch between smart targets and environmental goals
Much focus on ICT advancement and solutions efficiency and a lack of considering, if not ignoring, green urban design aspects
Advanced technologies used in smarter cities without making any contribution to sustainability
Smarter targets and environmental targets are not well understood despite their synergy
Misalignment between theory and practice and hence visions and implementations
Multiple ICT developmental paths and meanings of being smarter
Inconsistent sets of technological components comprising the infrastructure of smarter cities
Multiple future visions of smarter cities
Divergences in what constitutes smarter cities as to the relevance of the applications being offered
Socio-culturally oriented understanding, development, and implementation of smarter cities
Smarter technologies associated with pre-configured or pre-formatted solutions for yet-to-find urban problems, not with focused solutions for the environment
ICT research, innovation, and application directed mainly toward economic growth
A great deal of diversity among smarter projects, initiatives, and approaches

Adapted from Bibri and Krogstie (2017a)

10.2.2.3 Intellectual and Scientific Challenges

The most significant intellectual challenge facing the increasingly computerized urban world pertains to the idea that new socially disruptive technologies are not only developed to enable us to do and create new things and shape how we develop and revolutionize them, but also to study the processes of their own implementation and implication on cities—e.g., creating smart technologies for environmental sustainability and devising relevant assessment frameworks to measure or gauge how and the extent to which smarter cities contribute to and advance environmental sustainability. This is predicated on the assumption that technology and city as part of society re shaped at the same time in a mutual process, i.e., the former develops dependently of the latter, thereby affecting each other and evolving in that process, to draw on Bibri (2015b). As succinctly put by McLuhan (1964), we shape technology and thereafter it shapes us. This is the kind of challenge that needs to be resolved in the development of smarter cities that will enhance environmental sustainability. And future ICT of various forms of pervasive computing will unleash the kinds of sciences that can be mobilized to instigate profound changes in this regard. Accordingly, ICT of various forms of pervasive computing holds the key to an environmentally sustainable urban world, and this will be most clearly demonstrated in smarter cities. Toward this end, among the major scientific challenges to the development of smarter cities include the following:

To integrate and monitor the infrastructure of smarter cities and relate them to their operational functioning, planning, and development (in terms of physical structures, spatial organizations, ecosystem services, human services, and governance arrangements) through ICT of various forms of pervasive computing with respect to monitoring, analysis, evaluation, modeling, simulation, prediction, and intelligent decision support based on big data analytics and context-aware computing as a set of advanced technologies and novel applications for optimization, control, automation, management, strategy development, and policy design in the context of environmental sustainability. This entails connecting all urban systems, coordinating all urban domains, and amalgamating all urban services in ways that support and advance the goal of environmental sustainability. In this respect, the efforts should be directed toward demonstrating how developments in big data analytics and context-aware computing and the underlying core enabling technologies (namely sensor networks and infrastructures, data processing platforms, middleware architectures, and cloud computing infrastructures) can be integrated and harnessed so to make smarter cities more environmentally sustainable in the way urban planners, urban administrators, urban departments, and city authorities can use new technological applications, services, and capabilities for improving environmental sustainability.

To explore the idea of smarter cities as techno-urban innovation labs, which entails developing intelligence functions as new notions of operational functioning, management, and planning. These intelligence functions can, by utilizing data science, computer science, and complexity sciences in developing advanced simulation models and optimization methods, allow for monitoring and designing smarter cities with respect to the efficiency of energy systems, the improvement of transport and communication systems, the effectiveness of distribution systems, and the efficiency of ecosystem and human service provision in relevance to the environment. Such functions can take the form of centers for scientific research and innovation with the primary purpose of continuously improving the contribution of smarter cities to environmental sustainability thanks to the possibility of building models of real-time cities in terms of their operational functioning, management, and planning on the basis of sensor-based/machine-generated data.

To construct and aggregate many urban simulation models of different situations of urban life pertaining to the way existing urban systems can be integrated and urban domains can be coordinated integrated and collaborate, as well as to how human mobility data can be linked to spatial organizations, physical structures, transport systems and networks, and travel and commuting behavior, all in the context of environmental sustainability and its performance. And to explore and diversify the approaches to the construction and evolution of urban simulation models. This is to inform the future design of smarter cities on the basis of predictive insights and forecasting capabilities. This is becoming increasingly achievable due to the recent

advances in, and pervasiveness of, sensor technologies and their ability to provide information about medium- and long-term changes in the realm of real-time cities. To optimize physical mobility and to improve virtual mobility using ICT of various forms of pervasive computing in terms of combining big data analytics and context-aware computing in relation to reducing environmental impacts or improving environmental performance through low-carbon mobility. Thereby, both spatial and nonspatial accessibilities can also be enhanced in terms of city services and facilities.
To develop technologies that realize a better quality of city life in terms of air quality, water quality, waste reduction, public safety, and public health, which can otherwise be negatively affected by GHG emissions, pollution, and toxic waste disposal as direct impacts deriving from the ubiquity presence and massive use of advanced ICT in the context of smarter cities.

It can be inferred from the above challenges that most of the novel applications and services pertaining to ICT of various forms of pervasive computing and their positive impacts on the environment are still at the level of discourse in terms of the promises of, and claims for, an environmentally sustainable way of operating, organizing, and planning urban life. So, it remains to be seen the extent to which new technological innovation opportunities will be embraced and exploited, and their effects be realized and mainstreamed with regard to environmental sustainability in the realm of smarter cities.

10.3 Environmental Risks and Potential Mitigation Approaches

The prospect of smarter cities is becoming increasingly the new reality with the massive proliferation of data sensing, data processing, pervasive computing, and wireless networking technologies across the systems and domains of cities badging or regenerating themselves as smart. In this regard, smarter cities typically instantiate the prevalent ICT visions of pervasive computing with respect to what UbiComp, AmI, the IoT, and SenComp claim or aspire to deliver as to the future form of smart urban development (e.g., Bibri and Krogstie 2017a, b). In view of that, it becomes inescapable to avoid the multidimensional, adverse effects of ICT on the environment. Due to the scale of its ubiquity presence and massive use, ICT of various forms of pervasive computing shaped by the increasing application of, and driven by the growing demand for, big data analytics and context-aware computing as a set of novel technologies has a number of risks and uncertainties in relation to environmental sustainability that need to be well understood when placing high expectations on and marshaling huge resources for developing, deploying, and implementing smarter cities and their advanced applications. There exist intricate trade-offs and relationships among the positive impacts, negative effects, and unintended consequences of ICT in relation to the environment

(Bibri 2015b)—flowing mostly from the design, development, use, application, and disposal of UbiComp, AmI, the IoT, and SenComp technologies throughout smarter cities. Arguably, it is difficult to estimate the potential of ICT for advancing environmental sustainability in a meaningful way in the realm of smarter cities, as advanced ICT solutions involve technological innovation systems embedded in much larger socio-technical systems in which a complex web of factors and actors other than merely scientific and technical potential come into play. ICT sector's own emissions are increasing due to the growing demand for its advanced applications and services, especially those being offered by UbiComp, AmI, the IoT, and SenComp. The adverse environmental effects of these socially disruptive technologies are complex and intricate, and thus problematic to deal with. They include direct effects, indirect effects, rebound effects, systemic effects, and constitutive effects. These are detailed below together with the potential ways to mitigate the associated environmental risks.

10.3.1 Direct and Indirect Effects

Involving electronic components, sensors, devices, systems, processes, and infrastructures, UbiComp, AmI, the IoT, and SenComp technologies are associated with direct effects on the environment. Such effects derive from "the design, manufacturing, distribution, maintenance, and disposal processes of…[related] products, applications, and services by the ICT industry" in terms of "the energy used to make computer hardware and software, build facilities and maintain their operation, ship equipment, transport goods, provide multiple services" (Bibri 2015b, p. 174), and recycle e-waste. Adding to this is the material resource depletion in terms of extracting huge amounts of heavy metals and scarce elements, in addition to hazardous and highly toxic synthetic chemicals, water and toxic waste, electromagnetic radiation caused by wireless sensors, incineration of semiconductor-rich devices and systems, and so on (Bibri 2015b). This relates likewise to the design flaws inherent in the hardware and software components and systems of ICT due to many factors, including obsolescence, lack of incentives to design out e-waste, and lack of interest to adopt green design or sustainable product design (e.g., Forge 2007; Greenpeace 2005; Datschefski 2001; Abraham and Nguyen 2003). However, the direct effects of new technologies on the environmental will exacerbate due to the increasing demand for their applications, products, and services in the context of smarter cities as a future form of urban development, unless design for the environment as an approach gains momentum and becomes widely adopted during the transition of smart cities to smarter cities. Design for the environment seeks to eliminate potential negative environmental impacts before technological artifacts are made, whether in the form of hardware or software.

Direct effects are relatively easy to model, analyze, evaluate as well as design out. Indeed, the link between design and the environment is a close one.

Understanding this link has a central role in the design of environmentally sustainable human engineered systems, including technologies. However, the design of human systems has long overlooked environmental considerations, which has led to complex environmental problems, e.g., climate change, environmental degradation, and resource depletion. In particular, climate change is a visible instance that exposes the underlying flaws in the design of technological, industrial, and energy systems. It substantiates the unsustainability of the current destructive design trends. It is therefore time to rethink the relationship between such design and the environment to create environmentally sustainable human engineered systems, and thus technologies that can pave the way for restoring environmental quality in the realm of smarter cities.

Sustainable design has emerged as a general reaction to global environmental crises and damage to ecosystems (Shu-Yang et al. 2004). Its purpose is to eliminate negative environmental impacts through skillful, sensitive design (McLennan 2004). For the design of technologies to be sustainable, it has to stress efficiency, regeneration, resiliency, and sufficiency, as well as mimic natural designs, patterns, processes, and rhythms. Sustainable design is also referred to as "eco-design" (Papanek 1995). In the context of ICT of various forms of pervasive computing, eco-design can be conceived of as a strategy for mitigating the negative impacts associated with ICT product life cycle. Shu-Yang et al. (2004) contend that the practice of eco-design could potentially yield great environmental benefits. Eco-design is about realizing the potential of designers and benefiting from their creative abilities to drive technological innovations that help mitigate environmental risks and ultimately achieve the goal of environmentally sustainable development. Datschefski (2001) argues that environmental sustainability can only be achieved through design. Thus, the challenge for the design of ICT of various forms of pervasive computing is to embrace sustainable practices and principles for the pursuit of auspiciousness in smarter cities. Morelli (2007) claims that designers' perception is changing through the radical shift in the responsible role of technological and industrial companies. The new conditions imply a shift in the role of socio-technical regimes and thereby a mutation of designers' role. In all, sustainable/eco-design seeks to generate, extend, and replicate opportunities, protect natural ecosystems and the environment, and conserve and replenish scarce resources.

To reiterate, AmI as a computational technique can play a key role in the development of environmentally sustainable technologies. ISTAG (2003) points out that AmI can serve as a means in pursuing the development of new technologies that use fewer natural resources, in addition to optimizing energy efficiency and reducing pollution, thereby providing opportunities to mitigate the impact of the direct effects of the use of ICT by placing a greater emphasis on design for reuse and dismantling, as well as by introducing clean manufacturing using AmI processes in technology production.

Indirect effects arise from the use of UbiComp, AmI, the IoT, and SenComp applications and services across the systems and domains of smarter cities. In this regard, the environmental impacts of these technologies derive from the GHG emissions resulting from the intensive use of energy required to power a myriad of invisible, distributed, networked, interconnected, interactive, and always-on sensing and computing devices embedded in all kinds of everyday objects as part of the computationally augmented urban environment (Bibri and Krogstie 2016a) in order to enable the functioning of big data and context-aware applications and services in the context of smarter cities. Put differently, the operation of such applications requires a huge amount of energy to power sensor infrastructures, data processing platforms, cloud computing infrastructures, and wireless communication networks across the systems and domains of smarter cities. At issue is the design flaws inherent in the hardware and software systems of new technologies when it comes to energy consumption, as such systems are designed to be continuously improved for optimizing their energy efficiency (Bibri 2015b), which is driven by economic ends. This is applicable to energy efficiency technologies developed based on AmI, the IoT, and SenComp functionalities. Therefore, it is important to address and overcome the challenges of the unsustainability of ICT design methods in terms of energy-intensive use and concomitant GHG emissions risks relating to the use phase of the life cycle of ICT applications, products, and services—especially new technologies are projected to usher in automation in nearly all the domains of smarter cities, as discussed earlier.

However, the indirect effects of new technologies on the environmental are most likely to, like their direct effects, exacerbate due to the increasing demand for their applications, products, and services in the context of smarter cities as a future form of urban development, unless de-carbonization strategy becomes widely adopted and implemented during the transition of smart cities to smarter cities. De-carbonization entails designing less carbon-hungry or low power ICT equipment (e.g., energy on the fly instead of dependence on batteries using context-aware techniques), or exploring renewable energies (e.g., green computing). These are harvested or generated from natural sources that are essentially inexhaustible and naturally replenished. Renewable energy sources include solar, wind, biomass, geothermal, hydropower, oceanic, and photovoltaic, as well as integrated renewable solutions. The latter involves the use of analytical, management, and simulation techniques to enable a wide deployment of renewable energy. Here ICT is embedded in renewable energy technologies in the form of computing devices that monitor, model, and conserve the environment and thus mitigate the negative effects of anthropogenic involvement (Bibri 2015b). Worth pointing out is that AmI and the IoT are the mostly applied techniques in developing environmentally sustainable technologies (see Chap. 9 for more detail). As stated by ISTAG (2003, p. 11): “AmI can be instrumental in the development of new technologies that use fewer natural resources, optimize energy efficiency, and help reduce pollution or risks to health and safety… AmI can enable beneficial ‘secondary’ effects by reducing and optimizing physical mobility, by optimizing energy usage, and by improving waste management.” Indeed, “recent studies have estimated that potentially significant reductions in GHG could result from the use of ICT to improve the efficiency of transportation systems, and from the substitution of

Table 10.2 Sustainable product design and green design

Sustainable product design (Datschefski 2001)	Green design (Abraham and Nguyen 2003)
Solar: Their manufacture and use consumes only renewable energy that is cyclic and safe	Engineer processes and products holistically using environmental impact assessment tools
Safe: All releases to air are non-toxic	Ensure that all energy inputs and outputs are as inherently safe and benign as possible
Efficient: Most efficient use of energy required over life cycle	Do not be limited by current or dominant technologies; seek fundamental change

e-commerce and tele-work for their physical equivalents." (MacLean and Arnaud 2008, p. 5).

The philosophy of sustainable design is to design technologies as applications, products, and services that comply with the principles of environmental sustainability. Environmentally sustainable technologies are designed, developed, and used based on environmental philosophy or ecological intelligence. Here renewability is a central issue in terms of optimizing materials and using sustainably managed renewable sources. Table 10.2 presents examples of sustainable design principles (related to energy and emissions) from two engineering disciplines, namely product design and green design. Notwithstanding some slight variations between these disciplines, similarities draw from the focus on the use of renewable energy for product design and toxic emissions.

To date, much of the work that has been done on the relationship between ICT innovation and the environment has been focused on direct and indirect. In this regard, as started by (MacLean and Arnaud 2008, p. 5), "studies on the overall relationship between ICT, the environment, and climate change have generally shown that most positive effects of ICTs in reducing GHG emissions are likely to result from: a reduction in the carbon footprint of the ICT industry itself; the use of ICT to increase the efficiency and flexibility of energy production, distribution, and consumption; the use of ICT to increase the efficiency of production processes and facilities management; and 'dematerialization'—the substitution of virtual products and services for their physical equivalents."

10.3.2 Effects

It has been acknowledged that advanced ICT solutions result in increased energy consumption, instead of rationalizing or slashing it in other parts of the energy system, which relates to rebound effects (see, e.g., Bibri 2015b; Kramers et al. 2014). Such effects are the most challenging to come to grips with, as they involve socioeconomic, socio-behavioral, and socio-psychological factors. Advanced ICT improves the efficiency of the energy systems operating industrial machineries and engines, as well as optimizes the production processes of the industrial plants and facilities that produce UbiComp, AmI, the IoT, and SenComp technologies and their applications, products, and services. This entails energy efficiency based on sophisticated computational functionalities enabled by new technologies (context awareness, intelligence, decision automation, process control, etc.). This improvement, which results in reduced manufacturing costs and prices and thus increased purchasing power, leads to more demand for new technologies and their applications, products, and services given their economic gains (as well as social benefits) in the context of smarter cities. This leads to more negative impacts on the environment due to the consequent production and use of new technologies and their applications, products, and services. Similarly, an optimization of energy efficiency through new ICT applications (e.g., Herring and Roy 2007) based on computational processes pertaining to AmI and the IoT often results in an increase in energy consumption as a consequence of energy savings. For example, AmI and the IoT provide a lot potential to develop technologies that optimize energy efficiency in relation to buildings, appliances, and infrastructure monitoring. This results in acquiring more of the kinds of AmI- and the IoT-enabled energy efficiency systems and thus more production and more energy use across the value chain. Moreover, efficiency of energy resource decreases its price, which in turn results in increased demand and consumption of that resource that takes back all of the realized efficiency gains (e.g., Kramers et al. 2014). To further complicate the matter, energy efficiency triggers further ICT innovation and hence manufacturing, distribution, adoption, and disposal of energy efficiency technologies across the domains of smarter cities. Therefore, “GHG emissions reductions enabled by more advanced energy efficiency technology are likely to be minor, if not worsened, in the absence of parallel measures to manage demand for energy, which would in the normal course of events continue to increase due to the improvement in the performance of energy efficiency technology” (Bibri 2015b, p. 173). This is enabled by context-aware computing and big data analytics as forms of ICT of various forms of pervasive computing in the context of smarter cities. In a nutshell, while advanced ICT applications allow for energy efficiency, energy savings and thus GHG emissions reductions are potentially lost to greater energy consumption, thereby the failure to securing any efficiency gains. The interested reader can be directed to van den Bergh (2011) for other types of more complex rebound effects (time and space). Also, Nair et al. (2010) provide an overview of the factors (social norms, income level, energy prices, perception of energy cost, education, past investment, etc.) that influence energy efficiency investments in residential buildings as one of the application of AmI and the IoT technologies (see Chap. 9 for further details). Greening et al. (2000) provide a comprehensive literature review of the rebound effects and their taxonomy. In all, rebound effects constitute real conundrums to tackle whether in relation to the acquisition of new technologies or the associated energy efficiency applications under the prevailing economic model and urban development practice.

10.3.3 Systemic Effects

The challenge of systemic effects is a real dilemma in smarter cities for it is unlikely to be a "magic bullet" solution for their special conundrums. The systemic effects of ICT of various forms of computing are the most complex of all the aforementioned effects given their dynamic, volatile, multifaceted, and unpredictable nature. Indeed, particularly "direct and indirect effects—which are relatively easy to model, analyze, and evaluate—have, up to the present time, been the focus of much of the research work that has been carried out on the link between AmI, UbiComp, SenComp, and the IoT technologies, innovation, and environmental sustainability." (Bibri 2015b, p. 175) Systemic effects (e.g., MacLean and Arnaud 2008; Erdmann and Hilty 2010) arise commonly from changes in social, cultural, economic, and urban structures, practices, and behaviors triggered by the widespread adoption, ubiquity presence, and massive use of UbiComp, AmI, the IoT, and SenComp applications, products, and services (e.g., Bibri 2015b). The changes enabled and triggered by novel technologies will affect social, cultural, economic, and urban parameters in the context of smart er cities as to "the behaviors, attitudes, and expectations of consumers; citizens and communities; the demand and supply of AmI, UbiComp, SenComp, and the IoT services, products, and applications; manufacturing and distribution processes; organizational structures; and the various levels and forms of governance" (Bibri 2015b, p. 175). These parameters are linked to the constitutive effects of novel technologies in light of their deep embeddedness in the fabric of smarter cities and thereby changing the way they function and evolve. Seen from this perspective, the choices and decisions made by all urban constituents, including citizens, communities, organizations, and institutions about how to use novel technologies in the context of smarter cities "to change their behaviors and structures are unlikely to unfold or translate into behavioral and structural patterns that will play a potentially significant role in determining the possibility of successful…[smarter cities] response to the challenges of environmental sustainability" (Bibri 2015b, p. 175). In all coming to grips with systemic effects is a challenging task. "Clearly, there are linkages among actions taken to reduce the GHG emissions of the ICT sector; actions taken to reduce GHG emissions resulting from the application and use of ICT goods and services throughout the economy and society; resulting changes in the structure of economic and social activity; and global performance in terms of GHG emissions. However research and experience suggest that this relationship is unlikely to be linear; that the impact of ICTs is likely to be positive in some areas and negative in others; that its overall impact is not necessarily significant under current economic and social structures; and that alternative global governance options could significantly affect ICT impacts—for better or for worse—going forward." (MacLean and Arnaud 2008, p. 5). By and large, what is certain is that there is no certainty as to how to tackle the environmental risks posed by UbiComp, AmI, the IoT, and SenComp in the context of smarter cities.

10.3.4 Constitutive Effects

Constitutive effects derive from the deep embeddedness of ICT of various forms of computing in the very fabric of smarter city-urban systems, processes, and practices, to draw on Bibri (2015b). The is due to the fact that UbiComp, AmI, the IoT, and SenComp are integrative technologies in nature in the sense of becoming increasingly an integral part of almost every urban function, activity, service, and structure across all urban domains (e.g., Bibri and Krogstie 2016a). Hence, constitutive effects are too complex and intricate to tackle. As those socially disruptive technologies become a vital e-infrastructure for smarter cities, providing the key basic infrastructures for all vital urban systems and domains, they will dramatically increase energy consumption needed to operate such cities and maintain their functioning. This comes with concomitant environmental risks: the rise of GHG emissions as a direct result of devouring energy. The effects of such technologies on the environment of smarter cities will continue to escalate to the point of complete dependence on ICT of various forms computing for which there will be a penalty to pay in terms of the inherent environmental impacts as an externality to the constitutive effects of ICT.

Environmental sustainability is a complex, multidimensional issue, and it becomes even more intricate and problematic to deal with in the context of smarter cities given their characteristic features in terms of the ubiquity and massive use of ICT due to the associated multiple adverse environmental effects. Therefore, without careful deployment and implementation of the advanced solutions being offered by ICT of various forms of pervasive computing in combination and conjunction with other nontechnical measures, the novel big data and context-aware applications and services being proposed and directed for advancing environmental sustainability might result in devouring energy instead of slashing it in the other parts of the energy systems of smart cities, thereby worsening the concomitant environmental effects. Several "studies have suggested that the effect of ICT on GHG emissions in is likely to be minor in the absence of measures to alter demand. This is because of the central role the movement of physical goods and people plays in the economy and society, and the rebound effects likely to be triggered by factors such as increased demand resulting from lower prices, re-materialization, and the substitution of private for public transportation." (MacLean and Arnaud 2008, p. 5) Accordingly, in order to establish the full impact of advanced ICT solutions, it is important to take into account all the ensuing systemic and rebound effects and changes. This also points to the importance of combining the deployment and implementation of what big data and context-aware technologies have to offer as novel applications and services for the environment with policy and planning instruments, especially in relation to innovation and technology policy and environmental planning regulations, so as to ensure that the efficiency gains enabled by ICT of various forms of computing actually lead to curbing and reducing energy use and thus mitigating environmental risks.

The focus of legislative effort should be directed toward the implementation of more effective and innovative methods in the context of smarter cities, which can have more significant contributions to both energy conversation and GHG emissions reductions. Indeed, there is a need for new policy frameworks together with the implementation of mechanisms for adherence to or compliance with established regulatory instruments that ought to change the order of priority with regard to promoting and ensuring environmental protection and integrity in ways that enable optimum management of innovation, resource allocation, and public investment pertaining to ICT of various forms of pervasive computing in the context of smarter cities.

A holistic (systemic) analysis should be carried out on the intricate linkages between social behavior, social dynamics, socioeconomic relationships, and logics of ICT embeddedness and massive use in relation to the environment in the context of smarter cities. This is crucial to consolidating our current understanding of how to build urban forms for human settlements in ways that can strategically maintain their contribution to the goal of environmentally sustainable development, thereby providing upstream solutions for advancing environmental sustainability. In the context of smarter cities, policy design, planning, and decision made with regard to ICT of various forms of pervasive computing for environmental sustainability are to be based on such an analysis so as to devise meaningful instruments and strategic frameworks that can effectively affect urban constituents to make astute choices about how to use ICT to change their behaviors and relations. Drawing on MacLean and Arnaud (2008, p. 5) with reference to systemic effects, in order to fully assess the potential role of ICT of various forms of computing "in supporting the achievement of medium- to long-term targets for GHG emission reduction…, we believe it is necessary to come to grips with third-order effects by systematically identifying the kinds of changes in individual behavior, economic and social structures, and governance processes that would be needed to meet these targets; identifying the main policy issues associated with these changes; and assessing different options for responding to these issues, with a focus on the role of ICT-enabled innovation."

To make smarter cities environmentally sustainable, innovation is needed in all the systems and domains of such cities. This entails economic and governance models, institutional apparatuses and their techniques, social structures and relations, social rules systems, technology-push rationalities, and physical structures. While this may sound an unattainable goal or a daunting challenge, it is imperative for policymakers to be aware that the environmental effects of ICT on the environment are mostly due to the way technological innovations are being pursued, diffused, and used in contemporary cities, which are part of innovation systems that are embedded in the wider socio-technical landscape. Accordingly, transitioning to environmental sustainability as a manifestation of drastic shifts to sustainable technological regimes in the context of smarter cities necessitates concomitantly radical societal changes involving institutions, politics and public policy, and social values. Such shifts are difficult to get approved politically and entail decisions and priorities characterized by multiple levels of complexity (discussed further in the next section). Further to the point, having awareness of the underlying innovation factors and dimensions could, at least, serve to rethink future investments in the development and innovation of ICT of various forms of computing and their directions, and thus to rationalize future smart urban development endeavors by balancing between ICT-oriented energy reduction strategies and other energy conservation strategies (e.g., based on the typologies and design concepts of sustainable urban forms), thereby putting forward more realistic action plans to achieve environmental sustainability (see, e.g., Bibri 2013; Bibri and Krogstie 2017b). The main motivation for putting emphasis on innovation is that smarter cities are conceptualized as an interplay between scientific innovation, technological innovation, environmental innovation, urban planning innovation, institutional innovation, and policy innovation, representing and involving inherently complex socio-technical systems of all sorts of innovation systems focusing on the creation, diffusion, and utilization of knowledge and technology, including national, regional, sectoral, technological, and Triple Helix of university–industry–government relations, to draw on Bibri and Krogstie (2016a).

Future research on the relationship between ICT innovation and the environment needs to focus on the systemic and rebound effects of ICT of various forms of pervasive computing, which are more difficult to analyze, model, and evaluate, in order to be able to make ICT a key organizing principle for urban planning in terms of environmental sustainability. The prevailing assumption that ICT is capable of decoupling urban development from environmental degradation is, considering the way it is being designed, developed, used, and discarded, grounded in fallacies and paradoxes. Realistically, attempting to solve the unsettled issue of such complex effects should inspire or stir other alternative climate solutions, which may not necessarily lie within the boundaries of the prevailing ICT culture. Regardless, it is imperative to consider these effects when establishing the link between ICT innovation and environmental sustainability. Ignoring them will otherwise continue to disguise the dark side of ICT, to ignore its potential risks and uncertainties, and to quixotically place high expectations on it (Bibri 2013). Therefore, the problematic issue of systemic and rebound effects is worthy of attention and effort from policymakers that are struggling to figure out a way to manage the relationship between ICT innovation and the environment. Indeed, to come to grips with these two effects, it is first necessary to confront policy paradoxes (see, e.g., Bibri 2013; MacLean and Arnaud 2008).

10.4 Philosophical and Disciplinary Debates on Smarter Cities

10.4.1 Questioning and Challenging ICT-Driven Environmentally Sustainable Urban Development

The key questions involving the need for smarter cities to measure and identify environmental risks and uncertainties and then set safety standards accordingly relate to the philosophical perspective of sustainability science as an analytical framework, which pertains to the societal structures of material consumption. In relation to this, the increasing material consumerism, which has been enabled by science-based technologies, seems to have failed to bring environmental benefits in light of the way ICT is being designed, developed, used, and discarded. Bibri (2015b) provides a detailed analytical account of the implications of ICT of pervasive computing as advances in science and technology for environmental sustainability. Further, Huesemann and Huesemann (2011) demonstrate that technological optimism is grounded in ignorance, leading to uncritical acceptance and adoption of new (or socially disruptive) technologies. This involves the wide application and massive use of big data analytics and context-aware computing as a set of novel technologies and their applications and services in the context of smarter cities as future forms of urban development practices. The point is that whether in relation to urban development or other social practices, although ICT is inherently associated with adverse environmental effects that have been a subject of much debate for more than a decade and a half, not much effort has been done so far to contain such effects. This pressing environmental issue pertains mainly to the footprint of the ICT sector whose own GHG emissions are increasing due to the growing demand for its advanced applications, products, and services, especially those being offered by UbiComp, AmI, the IoT, and SenComp (e.g., Bibri 2015b). Related to the continuous development, application, and diffusion of these technologies, there are a lot of myths and oxymora that apply to the environmental subsystem of smarter cities where debates focus on the question of whether ICT of various forms of pervasive computing can actually accelerate and advance environmental sustainability, and how it can mitigate environmental risks, if it continues to be designed, developed, used, and discarded the way it has been hitherto.

It is very challenging, if not daunting, to evade the unintended consequences of the use of advanced ICT solutions in the context of smarter cities without the measures discussed above. In view of that, sustainability science must involve the role of ICT in aggravating the unsustainability of urban practices, just as in tackling the complex environmental challenges such practices generate, to draw on Bibri and Krogstie (2016a). In all, unless smarter cities can start getting reoriented in a more environmentally sustainable direction since they can not as envisioned and being currently practiced solve the complex environmental problems placed on the agenda of environmentally sustainable development, they risk becoming fallacies or paradoxes in the long term with respect to achieving the goal of environmental sustainability. Advanced solutions enabled by ICT of various forms of computing should in this regard be carefully implemented in conjunction with policy measures and planning instruments in order to yield the desired outcomes as to the environmental gains and benefits expected to result from the development, deployment, and implementation of smarter cities. Toward this end, it is important to underscore from the perspective of smart sustainable urban development that for such solutions to function constructively, concerted actions and collaborative efforts among city stakeholders are required. This should be guided by coordinating bodies and mayoral institutions with relevant governance roles as well as expert knowledge in order to strategically assess the implications of ICT innovations and investments pertaining to smarter cities, and thereby steer ICT development in ways that align with the agenda of environmentally sustainable development toward achieving the long-term goal of environmental sustainability within technologically and ecologically advanced nations (Bibri and Krogstie 2016a).

It is of high relevance and importance to question whether the model of ICT-driven environmentally sustainable urban development, the current object of urban planning fascination in the context of smarter cities, is useful to really guide urban planning practice concerning environmental sustainability. The discursive idea of ICT of various forms of pervasive computing in the sense of being socially constructed as having a catalytic and instrumental role in increasing the contribution of smarter cities to the goal of environmentally sustainable development in its current narrow construal seems to be vulnerable to the criticism of ideological symbolism and vague idealism. In this case, the symbolic and idealistic fascination appears to build upon a romanticized view of the prevalent visions of ICT—inspiring and far-reaching but of limited modern applicability. The respective model ought to be redefined and embedded into a broader understanding of socioeconomic and socio-political conflicts in technologically and ecologically advanced societies, so to become an influential and useful ethos for shaping urban planning with respect to environmental sustainability. Otherwise, it would symbolize an unproblematic, peaceful technological "ecotopia" in the information age and high-tech society.

10.4.2 The Meaning and Implication of ICT of Pervasive Computing for Urban Culture

Other philosophical questions concerning smarter cities revolve around the meaning of ICT for urban culture or the role of ICT in urban society, and what impact these issues have on how we understand and value environmentally (and socially) sustainable urban living. The discourse on smarter cities that has emerged over the last few years can be seen as "such a philosophical enterprise" (Shepard 2011). The view currently prevalent in this discourse is that, what is at stake in the ongoing debate is not so much the issue of how to build and engineer smarter cities equipped with computationally augmented environments with sentient, ambient, ubiquitous, and Internet-of-everything intelligence capabilities; rather, big data analytics and context-aware computing and related core enabling technologies may very well compel or propel us to rethink or alter some of the urban concepts through which we understand urban living—and value its environmentally sustainable dimension. As argued by Shepard (2011), the concept of sentient cities as instances of smarter cities relate to exploring how ICT of pervasive computing can be utilized to enhance our understanding of cities, or to describing its increasing role in the constitution of urban life. In other words, the central issue of cities becoming smarter does not merely lie in how to devise solutions for specific urban problems, automate routine functions serving particular buildings or transport systems, computerize parts of management systems or services, and enhance urban design and architecture methods by means of new technologies. Rather, the debate on smarter cities revolves around the profound impact of ICT of pervasive computing on the way we construct our lives in modern and future cities. This particular meaning of urban smartness lies in enabling us to find and use novel ways of understanding, probing, evaluating, and planning cities to advance environmental sustainability. These can occur through a variety of technical instruments, intelligence functions, and simulation models that can integrate, synthesize, manage, and analyze large-scale urban data for enhanced decision-making processes concerning not only the environmental form but also the social, economic, and even physical forms of cities. In all, the essence of the prevalent visions of ICT of pervasive computing in the context of smarter cities should lie in that the incorporation of computer and information intelligence into urban life and environments may well have positive effects on urban society, to draw on Bibri (2015b). Indeed, fundamental social, environmental, and practical questions have been raised regarding the role of ICT in shaping future cities (e.g., Crang and Graham 2007; Kyriazis et al. 2014; Shepard 2011; Shin 2009; Thrift 2014), especially in relation to different dimensions of sustainability.

The foreground of the normative facet of smarter cities goes with the grain of the discourse of smart sustainable urban development that plays a shaping role in the debate on such cities. In the urban context, the word “sustainable” as a socially constructed concept essentially concerns normative values, and thus implies a certain desired state of the city and hence the trajectory of its development. In a similar vein, the word “smart” has been seen as an intended outcome (Bibri and Krogstie 2016a) rather than as an instrumental concept. As such, it becomes just as normative as sustainable (e.g., Höjer and Wangel 2015). This conclusion can not though be that simple, as what is smart is not necessarily sustainable as has been the case for smart cities over the past many years (e.g., Ahvenniemi et al. 2017; Bibri and Krogstie 2017a; Höjer and Wangel 2015; Kramers et al. 2014).

10.4.3 Encounters of ICT Use and Application in Urban Planning and Development

As to disciplinary debates, the prospect of smarter cities is evolving into scholarly and realist enterprises (e.g., Bibri and Krogstie 2016a, 2017b), marking a key point in the history of urban planning and development—at which the disciplinary debate on how to use and apply smart ICT and merge it with urban systems goes beyond the boundaries of the involved urban professions, including landscape architects, planners, and engineers. In addition, the urban actors or players promoting sustainable city projects and initiatives are most likely to consider that engaging with the more challenging technological aspects as to making urban living more environmentally sustainable is beyond the scope of their expertise. This holds true in both cases since ICT integration, coordination, deployment, and implementation involve sophisticated digital technologies and their applications (e.g., urban sensing, urban informatics, big data analytics, context-aware computing, middleware architectures, cloud computing infrastructures, and wireless communication networks). The hopes of many contemporary scholars and practitioners of urban and environmental planning and policymaking processes as part of ongoing negotiations and, even, disputes are extended to a wider debate over the upcoming urban transformation as driven by the increasing technologization and computerization of urban society. With this fact in mind, ICT must be exploited and leveraged in the needed transition toward and advancement of environmentally sustainable urban development.

10.5 The Effect and Potential of ICT of Pervasive Computing for Advancing Environmental Sustainability

10.5.1 On the Productive and Constitutive Force of ICT of Pervasive Computing

The increasing adoption of UbiComp, AmI, the IoT, SenComp in smart and smarter cities, coupled with the ongoing intensive research, development, and innovation in academia and industry reflects the productive and constitute force of these novel technologies in relation to environmental sustainability, among other things. Implying a drastic shift in such dimensions as citizens and urban entities as the use of new technologies, the prevalence of novel applications and services across diverse urban domains, and the urban players involved, and the scale of the emerging ICT industry consortia and urban markets, ICT of various forms of pervasive computing for environmental sustainability as a productive and constitutive network operating on all the scales of smarter cities not only produces new objects of knowledge in the form of sciences, disciplines, philosophies, rationalities, strategies, and practices, but also generates technological artifacts, orientates technological innovations, steers technological investments, catalyzes transformations, shapes institutional developments, constitutes institutional bodies, and creates and regenerates new urban environments in the realm of smarter cities, to draw on Bibri and Krogstie (2016a). This power manifested in a productive and constitutive network runs through the whole body of such cities, to draw on Foucault (1980).

Remaining on the same topic, huge investments are being funneled into smarter city projects and initiatives, and considerable resources are being mobilized for smart urban planning research in big data in relation to city analytics and context awareness in relation to urban computing for advancing the operational functioning and planning of smarter cities in line with the vision of environmental sustainability, among other things. The evolving expansion of ICT of various forms of pervasive computing as directed for environmental sustainability through particularly the expansion of smarter city projects and initiatives demonstrate increasing returns and benefits from the adoption of UbiComp, AmI, the IoT, and SenComp as new technologies in diverse urban domains. These technologies benefit from the provisioning of new applications and services in response to the new urban market demand as well as to the growing intention of capturing further and invigorating the application demand for the environmental sustainability solutions and approaches that ICT of various forms of pervasive computing can offer. This signifies that such technologies exhibit positive feedbacks such that the more they are deployed and implemented in relation to smart and smarter cities, the more likely they are to be further deployed and implemented (see, e.g., Arthur 1989; North 1990). Social apparatuses “behind this phenomenon commonly entail network effects, scale, adaptation, and learning, which fuel or stimulate further adoption of such technologies.” (Bibri 2015b, p. 140) New urban policies supporting research and innovation within the domains of ICT of various forms of computing are increasingly being developed based on big data analytics (see Chap. 4 for more details), “and more of policy networks are being formed because of the benefits expected or estimated to be gained from the significant opportunities for” (Bibri 2015b) UbiComp, AmI, the IoT, and SenComp in relation to improving the urban model in terms of environmental sustainability on the basis of big data analytics and context-aware computing (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Shepard 2011; Kyriazis et al. 2014; Solanas et al. 2014).

10.5.2 Large-Scale Deployments of UbiComp, AmI, the IoT, and SenComp Driven by Environmental Gains

Data-centric and context-aware solutions enabled by ICT of various forms of pervasive computing have proven track records for enhancing the environmental sustainability of smart cities (e.g., Al Nuaimi et al. 2015; Batty et al. 2012), as well as offer prospects for smartening up sustainable cities as to their contribution to the goal of environmentally sustainable development (e.g., Bibri and Krogstie 2017a, b; Höjer and Wangel 2015; Kramers et al. 2014; Shahrokni et al. 2015). This implies that the ability of monitoring, understanding, probing, and planning smart and sustainable cities can be leveraged in the advancement of environmental sustainability, thereby the call for directing the potential of ICT of various forms of pervasive computing for this purpose in the context of smarter cities as future forms of urban development. Indeed, large-scale deployments of smarter cities based on UbiComp, AmI, the IoT, and SenComp are being justified mainly by the environmental benefits that are expected to be gained in the medium and long term. Such deployments are happening across the world in parallel with the construction of big data processing platforms and middleware architectures for context-aware computing to improve urban operational functioning, management of urban systems, and urban planning in line with the goal of environmentally sustainable development (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a, 2017a, b; Shepard 2011; Kyriazis et al. 2014; Solanas et al. 2014). See Chap. 8 for an account of large-scale deployments of ICT of various forms of computing in the context of smart and sustainable cities.

Among the environmental advantages of smarter cities when combined with sustainable urban forms are the following, to draw on Bibri and Krogstie (2017a):

Context-aware and data-centric applications for enhancing the contribution of the typologies and design concepts of sustainable urban forms to the goal of environmentally sustainable development;
Sophisticated data-centric methods for evaluating and substantiating the practicality of these typologies and design concepts as to their contribution to this goal;
Data-centric methods for comparing various sustainable urban forms as to their contribution to this goal;
Advanced models for urban design scalability, urban functioning efficiency, and urban planning flexibility necessary for responding to urban growth and related environmental pressures;
Advanced tools and methods for realizing a dynamic conception of sustainable urban forms in terms of processual outcomes of urbanization in connection with tackling environmental issues in a more effective manner;
Innovative models for smartening up the metabolism of sustainable urban forms to sustain their levels of environmental sustainability;
Context-aware and data-centric applications for integrating and enhancing urban systems and facilitating collaboration and coordination among urban domains in the context of sustainable urban forms;
Relating the typologies and design concepts of sustainable urban forms to their operational functioning and planning through ICT of various forms of pervasive computing with respect to monitoring, management, control, automation, and optimization;
Exploring the idea of sustainable urban forms as innovation labs on the basis of urban intelligence functions;

Diversifying modeling approaches into building and aggregating urban simulation models to inform the future design of sustainable urban forms based on forecasting or prediction capabilities;
New ways of understanding and addressing environmental problems;
Identification of all kinds of environmental risks, uncertainties, and hazards concerning sustainable urban forms; and
Better management and planning of resources, infrastructures, networks, facilities, and services in terms of energy efficiency and GHG emissions reductions.

10.5.3 Applications of ICT of Pervasive Computing for Environmental Sustainability

Significant opportunities exist for UbiComp, AmI, the IoT, and SenComp—and hence big data analytics and context-aware computing—in relation to advancing the model of smarter cities in terms of the environmental dimension of sustainability, as the range of urban application areas that utilize these advanced technologies in connection with environmental sustainability is potentially huge. In other words, such technologies usher in automation and intelligence in nearly all urban domains. Related applications include the following (Bibri and Krogstie 2016a, 2017a, b):

Energy efficiency;
Carbon footprint reduction of the ICT industry;
Energy production, distribution, and consumption flexibility;
Industrial production processes efficiency;
Dematerialization and demobilization;
Environmental monitoring and protection;
Transport systems efficiency and management;
Water and waste management;
Water supply and distribution networks effectiveness;
Power grid management;
Low-carbon and virtual mobility;
Urban infrastructures and facilities monitoring and management;
Noise and pollution reduction;
Zero-emission and low-carbon buildings;
Natural ecosystems management;
Resource utilization efficiency;
Traffic management and street light control;
Public safety and civic security (natural disasters and environmental crises);
Public health (air and water pollution); and
Ecosystem service provision efficiency.

There are fascinating possibilities and immense opportunities to embrace and realize from deploying and implementing the advanced solutions being offered by ICT of various forms of computing directed for environmental sustainability, which entails exploiting the benefits, capabilities, and innovations of big data analytics and context-aware computing to advance smarter cities in this direction. This can well be achieved if ICT development can be linked to the agenda of environmentally sustainable development, and ICT investment is justified by the pursuit of overcoming the challenge of environmental sustainability.

10.5.4 The Untapped Potential of Big Data Analytics and Context-Aware Computing for Advancing Environmental Sustainability

There has been much enthusiasm about the immense opportunities provided by new and more extensive sources of urban data to better operate, manage, plan, and develop cities to improve their contribution to the goal of environmentally sustainable development. Smarter cities as complex systems, with their domains being more and more interconnected and their processes highly dynamic, rely typically on sophisticated technologies to realize their potential for responding to the challenge of environmental sustainability. The most prevalent and influential of such technologies are big data analytics and context-aware computing, which are rapidly gaining momentum and generating worldwide attention in the domain of smart sustainable urban development (Bibri and Krogstie 2017a). Context-aware behavior and big data capability are considered as prerequisites for realizing the novel applications pertaining to UbiComp, AmI, SenComp, and the IoT in the context of smarter cities.

The use of big data analytics and context-aware computing technologies as a set of powerful techniques, methods, and models offers the prospect of smarter cities in which natural resources can be managed and planned safely, sustainably, and efficiently in an intelligent way. Indeed, significant opportunities exist for these two technologies in relation to adding a whole dimension to the model of smarter cities in terms of environmental sustainability. The range of urban application areas that utilize big data analytics and context-aware computing in connection with the goal of environmentally sustainable development is potentially huge, as these two advanced forms of ICT usher in intelligence and automation in some many sub-domains of nearly all urban domains. Hence, the opportunities for combining big data analytics and context-aware computing technologies are enormous due to the role they will play in several important sectors of smarter cities.

As a research direction, big data have recently attracted scholars and scientists from diverse disciplines, as well as practitioners from a variety of professional fields due to their prominence, in relation to smart, smarter, and sustainable cities, especially in the domains of environmental planning, transportation engineering, sustainable mobility, infrastructure management, and public health, in addition to being a major intellectual, scientific, and practical challenge (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri and Krogstie 2017a, b). Big data analytics and context-aware computing capabilities hold tremendous potential to revolutionize urban analytics and computing in relation to sustainable planning and development. In the spirit of the evolving paradigm shift in urban planning and development, manifested in the rise of smarter cities, advances in such capabilities will make it possible to address the challenges of environmental sustainability and urbanization in ways that were, in many cases, not conceivable, even a decade ago.

10.6 Moving Beyond the Visions of Smart Cities: Rethinking Prevailing Assumptions and Embracing Alternative Research Directions

The prevailing conceptualization of smart cities sees them as being responsive to the beneficial impacts resulting from the deployment and implementation of ICT. Smart city thinking currently sees ICT of various forms of pervasive computing as offering the ability to collect, store, integrate, manage, process, and analyze data to mainly enhance the efficiency and effectiveness of cities through smart solutions. Smarter cities represent an urban model or urban development approach that joins up thinking around both augmented smartness and environmental sustainability. Smart cities therefore need during their transition to smarter cities to leverage their informational landscape to establish and maintain an environmentally sustainable approach to development, streamline and improve physical and infrastructural systems, reinforce resilience to natural disasters, mitigate the impacts of environmental pollution and pollutants originating in anthropogenic activities, and underpin well-balanced and appropriate adherence and regulatory mechanisms based on multi-scale governance, in addition to enhancing the quality of life and well-being of citizens in terms of environmental quality (and many other relevant aspects related to social sustainability as discussed in several chapters of this book) and ensuring responsible and tangible economic development.

Not long time ago, an increasing number of researchers/scholars in the field of smart cities have started to question the dominant assumptions as well as the driving forces behind the visions of smart cities, particularly the strong ICT orientation view underlying most of the envisioned scenarios, which are associated with the evolving smarter cities as well. This pertains to the sole and core focus on technical advancement and solutions efficiency as driven sorely mostly by economic gains and financial performances. The key reason why this is taking place is essentially because there has been a growing realization that ICT—through becoming embedded in the very fabric of contemporary cities, i.e., an integral part of urban life and thereby increasingly facing the urban reality and related sustainability and urbanization conundrums that will eventually shape its evolution in cities of the future—could do a lot to accelerate and advance environmental sustainability in the years ahead. Especially, smart cities are, by all indicators, evolving into smarter cities, which typically rely on ICT of various forms of pervasive computing that holds that potential. This calls for a shift from focusing on technological perspectives in the sense of favoring technical advancement of ICT without linking it to environmentally sustainable development to exploring new windows of opportunity for aligning ICT development with environmental change. The basic idea is that it is time for smart cities to move beyond the technological view as its founding vision and embrace environmental sustainability as an important emerging trend that may bring the field of smarter cities closer to realization, delivery, and real environmental impact. This is anchored in the underlying assumption of the constitutive and integrative nature of ICT of various forms of pervasive computing in relation to urban systems and domains that may give a new boost to smarter cities to evolve into urban development strategies that can provide a substantial contribution to the goal of environmentally sustainable development, and that their adoption can therefore be further spurred and widened. This is in the spirit of following the path pursued by existing models of sustainable urban form as instances of sustainable cities, whose development, implementation, and improvement have been active since the inception of the notion of sustainable development in the late 1980s and its immediate application to urban planning and development in the early 1990s to achieve the required level of sustainability.

The visions of smart cities have mostly revolved around the idea of both tightly integrating ICT with urban systems and thus computerizing and automating all kinds of the underlying functions, operations, and services across a wide variety of urban domains. This has resulted in an alphabet soup of smart city approaches (Bibri and Krogstie 2017a), which has in turn generated a cacophony that has led to an exasperating confusion in the field of smart cities, despite the convergence on the idea that ICT constitutes a central focus in urban operational functioning and planning. Over the last decade, the visions of smart cities, albeit their variations as to the technical detail and area of focus, have overall tended to prioritize technological competitiveness while only passing reference to the role of ICT in addressing the challenge of environmental sustainability. That is to say, these visions remain less explicit and less goal-oriented—as to environmental sustainability, but more technologically oriented and driven. Indeed, much of the literature highlights the focus on ICT advancement and potential in relation to economic growth and the quality of life as key features of smart cities, to reiterate. But the literature addressing the role of ICT in improving environmental sustainability highlights that the goal of environmentally sustainable development is not explicitly incorporated in most of the concepts of smart cities, as mentioned above.

After almost two decades of considerable research and practice effort for developing and implementing smart cities programs and initiatives (scattered projects though), it is now timely to look back at visionary scenarios, the research endeavors undertaken and the related results accumulated, and reflect on the overall achievements of the field of smart cities with respect to their contribution to the goal of environmentally sustainable development. Important to note is that it is roughly since 2008, after the emergence and institutional support of the European smart city projects, when the number of scholarly writings and academic publications on the topic of smart cities has considerably increased (Jucevicius et al. 2014), with the consideration that the concept of smart cities was first introduced in 1994 (Bibri and Krogstie 2017a; Dameri and Cocchia 2013). Regardless, it is safe to recognize that researchers and planners in the field of smart urban development have now gained a much more thorough understanding of the problem domain and alternative solutions to the specific issues involved, as well as the misconception and deficiency issues that smart cities raise with respect to their role in improving environmental sustainability. It is also of significance to acknowledge the existence of the persistent and large gaps between the promises and claims of smart cities, which were made around the mid-2005s, and their real achievements concerning their contribution to the fundamental goal of environmentally sustainable development. This suggests that it is of high relevance to direct smarter city endeavors and initiatives right from the start toward advancing environmental sustainability. Especially, the central feature of smart cities, namely their focus on and orientation toward technology and its advancement and potential only, is being increasingly questioned and challenged, as such cities are falling short in considering urban urgencies and ignoring the environmental pressures being engendered by the rapid urbanization of the world, thereby failing to take a holistic approach in terms of linking ICT development with urban development and environmental change.

From its inception, the field of smart cities has always been strongly driven by particular visions of how ICT would shape future urban culture. These visions of the future are compelling and stimulating because they have proven to embody the power that catches people's imagination and challenge them to think outside common mindsets and look for new opportunities. In relation to smart cities, these visions have inspired many researchers and practitioners from diverse academic and professional fields respectively into a quest for the numerous opportunities enabled and created by the incorporation of ICT in the systems and processes of modern cities and thus using computer and information intelligence in organizing and operating urban life. Of importance to underscore when it comes to the visions of smart cities is the idea that the potential of ICT for reshaping urban culture has been shown to mean to also promote debate and reflection over what ICT can offer to sustainability, and how and the extent to which we need to capture further and invigorate the application demand for the sustainability solutions that advanced ICT can offer. In this spirit, the visions depicted by smart cities ought indeed to take into account the potential of ICT for advancing environmental sustainability given the constitutive and integrative nature of ICT with respect to urban domains, to reiterate. In these visions, for many environmental problems and challenges, there are technological solutions to explore and apply, if ICT can be strategically and intelligently exploited, thereby the call for embracing this untapped potential in the transitioning to smarter cities. These cities promise drastic transformations on the basis of the breakthroughs enabled by ICT of various forms of pervasive computing, which are indeed enticing and motivating in the event of the new strongly disruptive technologies permeating the urban world. They are apt to live up to expectations mainly because of the potentially complete integration of ICT and environmental sustainability. The premise is that as smarter cities will place a strong focus on the new features enabled by ICT of various forms of pervasive computing, they are well suited to pay enough attention to the environmental perspective around these features and their wide adoption across urban systems and domains. This is typical of the stage in which smarter cities are emerging and the underlying ICT is developing, and thus not yet operating and available. In this regard, the visions of smarter cities should reflect realistic assumptions about the evolution of environmentally sustainable development practices, as well as about the complexity and scalability of cities in their own social context (see Bibri and Krogstie 2016a). They should moreover go beyond mimicking existing urban operational functioning and planning to include the envisioning of the disruptive nature of ICT innovations pertaining to environmental sustainability. Thereby, the challenges of the present and the ensuing issues are not neglected or postponed but rather solved and tackled in the working toward the visions of smarter cities. In addition, the visions of smarter cities should converge on multiple visions of the future so to not exclude alternative visions in their evolution, i.e., promote the convergence of multiple efforts toward environmental sustainability as a shared goal, thus contributing to make it more achievable or reachable. Smarter cities constitute a field where a wide range of scientific, technological, and academic areas come together around a common vision of the future, which should embrace environmental sustainability and the immense opportunities such future will bring.

The field of smart cities has not matured yet to the point of taking stock of the available body of interdisciplinary research, as well as of enabling incremental research in this regard. The latter is a cornerstone for any research area. Moreover, the peculiar research field of smart cities in its continual formation and reformation highlights the nature of the involved challenges stemming from the nature of interdisciplinary inquiry as a continuation of long-lasting scientific, technological, and urban cooperation across diverse disciplines. This pragmatic and democratic notion of collaboration is akin to how sailors at sea rebuild their boat in ways that enable them to start from scratch and to have recourse to an overarching plan. This implies a continuous construction or formation of smart cities. Continually emerging, smart cities are in a state of recurrent flux due to new technologies and their migration into new urban application domains, and concurrently striving to build technologically useful conceptualizations. Indeed, being not a well defined and remarkably heterogeneous research area, i.e., elusive inquiry objectives and diverging research programs, smart cities are becoming increasingly fragmented. As a consequence, the research field of smart cities is unable to proceed in anything like a cumulative fashion and hence unable to contribute systematically and constructively to the design and development of advanced technologies, including those that can support the environment. To add, most of the so-called smart technologies are being used in smart cities without making any contribution to environmental sustainability. Further to the point, different research opportunities and programs have little in common, apart from a shared orientation toward smart solutions, exploring different horizons and addressing different problems respectively. Also, research programs are conceived of in different conceptual models and frameworks and employing largely disparate research methods and techniques. In all, the mutual indifference of the different research opportunities and programs in the field of smart cities is an indication of fragmentation, which is detrimental to the field. The rationale is that this fragmentation makes it exceedingly difficult to work in a cumulative manner for researchers and scholars as well as in a collaborative manner for urban planners and ICT experts in the field, adding to fostering and exacerbating confusion within it.

In light of the scientific discovery and technological innovation underlying ICT of various forms of pervasive computing, coupled with the established knowledge of urban sustainability in terms of theoretical foundations and practices, it is time to proceed with an effective amalgamation of these two areas given their synergy and complementary nature, more precisely directing the disruptive and transformational power of ICT toward advancing environmental sustainability in the ambit of smarter cities as a future form of city development. As a mature field of research, environmental sustainability as a component of sustainability science and a dimension of urban sustainability is concerned with the complex mechanisms and behavioral patterns involved in the profound interactions between the environmental and urban systems that can lead either to systematic degradation or sustained provision of such systems, and thus concomitant perils or benefits to the environment. In the realm of smarter cities, environmental sustainability involves how those interactions affect the associated challenge as to substantially preserving the urban ecosystem by tackling the continuing decline in resources and lessening pollution and waste levels, while improving the quality of urban life by providing clean air and water and human environment that maintains public health and safety. As an interdisciplinary academic discipline burgeoning in an increasingly technologized, computerized, and urbanized world, environmental urban sustainability can point the way to smarter cities with sustainability vision by essentially harnessing and exploiting ICT of various forms of pervasive computing in ways that allow for finding, employing, and mainstreaming more innovative solutions and more sophisticated methods for identifying and overcoming the complex challenges pertaining to environmental sustainability in the years ahead. This entails strategically directing the transitioning process of smart cities to smarter cities toward advancing environmental sustainability by capitalizing on what ICT of various forms of pervasive computing can offer as novel ways of translating environmental sustainability into concrete projects and strategies related to the built, infrastructural, operational, and functional forms of the city. This endeavor entails taking stock of what has been learned and accumulated as substantive knowledge on how ICT has contributed so far and the extent to which it can further contribute to environmental sustainability toward creating an integrated research field and applying the resulting interdisciplinary knowledge more effectively to not only address the challenge of environmental sustainability, but also accelerate and advance it in the context of smarter cities. This represents the achievement of the goal of environmentally sustainable urban development with support of emerging and future ICT of various forms of pervasive computing under what smarter cities.

It is most likely that a growing body of research findings and solved challenges pertaining to environmental sustainability will be witnessed during the transitioning process of smart cities to smarter cities. Important to note is that the inter-linkages across (and conflicts among) the fundamental goals of sustainable (urban) development have been, and will always be, if not a daunting then surely challenging but intriguing area of socio-technical research and innovation in the realm of every conceivable city approach as an urban development strategy. Moreover, it is crucially important to advocate the use of sustainability science as an overarching concept and ICT of various forms of pervasive computing for environmental sustainability as a form of science and technology for informing urban policy and administration, especially in relation to monitoring and harmonizing environmental sustainability indicators and targets on the basis of big data analytics and its innovation (see Chap. 5 for more details). This requires focused political mechanisms and effective governance arrangements for compliance with or adherence to appropriate regulatory instruments and frameworks, as well as in-depth cost-benefit analyses when designing such instruments and frameworks.

The idea that computer and information intelligence will be in the most diverse scenarios of urban life, enabling new forms of urban intelligence functions and drastic transformations in relation to the way urban systems function and can be managed, planned, and development, as well as how urban domains can be coordinated and integrated in the context of smarter cities is beginning to happen today. However, we must also acknowledge that the nature of the applications and services that will constitute smarter cities are but advanced forms of the applications and services pertaining to smart cities in terms of the efficiency and effectiveness associated with economic growth and the quality of life. But new applications and services ought to be directed toward improving the goal of environmentally sustainable development. In addition, the prevailing applications and services of smarter cities today may turn out to be very different from what we are currently envisioning. And while smarter cities should consequently not get stuck to particular visions of the future, they should link the development of their associated applications and services with environmental concerns. In this regard, a core part of the research field of smarter cities becomes able to proceed in a cumulative fashion and hence able to contribute systematically and constructively to the design and development of advanced technologies supportive of the environment. The field of smart cities is still strongly anchored in the visions that lead to their emergence, and therefore questioning those visions may easily seem like questioning smart cities themselves. However, revisiting the visions of smart cities and questioning some of their assumptions should not be seen as a recognition of failure or even criticism to the field of smart cities. Instead, it should be seen as an integral part of the research progress in which visions of the future should not be seen objectives in themselves, but rather as a starting point from which we depart toward realization, which can clearly be demonstrated in smarter cities. Hence, moving beyond the visions of smart cities when transitioning to smarter cities should be viewed as a way of adopting a clearly focused approach and as a sign of progress that visions have already fulfilled their role and realized what can be attainable, and that the field of smarter cities is now ready to take over and aim for something bigger in terms of advancing environmental sustainability. Also, moving beyond the visions of smart cities and embracing the visions of smarter cities signify primarily fully understanding the meaning and implications of what smart cities represent and of what smarter cities seek to bring as real added value. At least at the level of discourse, the visions of smarter cities clearly highlight the importance of a more holistic view that considers the environment and other nontechnical challenges associated with urbanization as crucial when transitioning to smarter cities, more specifically these visions need to be driven by environmental concerns, not technologically determined ones. ICT has already gained a clear predominance in smart cities, but the field of smart cities is now at a tipping point, where new objectives should be formulated and expectations must be confronted with reality in terms of environmental sustainability and environmental pressures engendered by the unprecedented rate of urbanization. ICT of various forms of computing is already enough to do much more than what has been achieved thus far, and hence smarter cities can no longer be driven by only technical advancement and overblown research agendas focused mainly on efficiency aspects. Smarter cities should develop new pathways and roadmaps toward delivering powerful applications and valuable services supportive of the environment for the urgent issues and for the messiness of an increasingly urbanized, unsustainable urban world.

10.7 On the Transition Governance of Smarter Cities—Innovative Technological Strategic Niches

The extent to which smarter cities could be achieved as envisioned with respect to environmental sustainability can be valuably explored by drawing on research within transition governance and innovative technological strategic niche development. In particular, within social studies of new technologies, which are concerned with the transformation of technological regimes, it is emphasized that innovative technological strategic niches play a role in transition governance (Rip and Kemp 1998; Smith 2003; Geels 2005). Often debated in reference to sustainable development as an alternative model of environmental governance and its possible use as an approach to instigating major changes (Bibri 2015b), transition governance aims to direct the gradual, continuous transformational process of socio-technical practices and socio-political landscapes from one equilibrium to another (Rotmans et al. 2001; Meadowcroft 2009). A transition of an urban kind denotes a change from a socio-technical landscape or technological regime associated with the city to another. Further, transition governance indirectly influences and redirects the choices and decisions of strategic actors toward achieving different goals of sustainability, instead of seeking to control the uncertainties of sustainable change, to draw on Loorbach (2007). This is of particular relevance to smarter cities as a form of urban change with regard to environmental sustainability. In this respect, transition governance seeks the outcome of the change to mitigate inherent uncertainties, augment resilience capabilities during the transformation of socio-technical regimes or systems, and generate desirable or anticipated socio-political outcomes (Rotmans et al. 2001; Meadowcroft 2009). This can, for example in relation to the potential of ICT of various forms of pervasive computing for advancing environmental sustainability in the context of smarter cities, be attained by engaging various urban stakeholders on multiple scales to create shared visions that are, in fact, currently being investigated and tested for practicality and viability through the use of such diverse mechanisms as experimentation, learning, adaptation, and network effects at the niche level with regard to big data analytics and context-aware computing as a set of novel technologies and their novel applications.

In general, the key premises of transition governance include: taking a multi-actor approach to encompass worldviews and societal values and beliefs, thereby widening the participation of actors within governance; espousing a system approach in terms of recognizing that problems span multiple actors, levels, and domains; taking a long-term perspective generating a basket of visions; and focusing on learning at the niche level through learning by doing and doing by learning (Loorbach 2007; Rotmans et al. 2001). Multi-actor approach is of particular importance in the process of transition governance. In this respect, the main rationale behind espousing multi-scale governance is that a limited number of actors will often fail to identify one vision that will get purchase from, or be accepted by, all and sundry, as it is a plurality of visions that is appropriately needed, which entails sharing common factors that can be established for further development, adding to the potential role of wide involvement of actors in attracting broader consensus and stronger advocacy and thus less resistance to, and disagreement on, the transition (e.g., Rotmans et al. 2001). Indeed, too much convergence on one vision or a few visions may end up excluding alternative visions, which is a significant risk to consider, thereby the value of promoting the convergence of multiple efforts and thus actors toward common goals associated with the transition to smarter cities, thus contributing to making them more reachable. Moreover, polycentric systems are necessary to cope effectively with complex problems of modern society, and to give all its constituents a more effective role in its democratic governance, to draw on Ostrom (2000). In terms of power relations, power within the process of transitioning to smarter cities via more sophisticated technologies is still distributed within the network governance (as a mechanism of coordination) concerned with the transition in question; all actors (e.g., industries, policymakers, research institutions, universities, civil society organizations, etc.) play a "socially-negotiated" part in shaping that transition (Bibri 2015b). This implies that power is not necessarily equally or equitably distributed, thereby the need to involve a wide selection of participants within the transition process, which leads to different forms of interaction and transition due to the dynamics and processes generated by the mixture of the power and relationships among the actors within smarter cities as forms of social organization. The (pragmatic) power distribution, however, allows for both the process of mutual adaptation toward shared goals pertaining to the transition as well as the emergence and evolution of self-organized and -regulated socio-technical trajectories (Kemp and Parto 2005). Regardless, the reflexive approach of transition governance "still lacks any real sense of the politics and power relations involved between the different actors and institutions that may facilitate or hinder the transition… Transition is therefore not inevitable, but the outcome (or not) of struggle, agency, and power relations" (Gibbs 2009, p. 69).

Furthermore, transitions denote changes from one socio-technical landscape, regime, or system to another. Socio-technical regimes entail "interconnected systems of artifacts, institutions, rules, and norms" (Berkhout et al. 2003, p. 3), an extended version of Nelson and Winter's (1982) definition of the term: shared cognitive routines or (frames of mind) in an engineering community, and also explanation of patterned progress along technological trajectories. This explanation has been broadened with the argument that policymakers, scientists, advocacy or special-interest groups, and users also contribute to patterning and planning of technological development (Bijker 1995). This pertains, in this context, to aligning the advancement of ICT of various forms of pervasive computing with the advancement of environmental sustainability in the realm of smarter cities. Further, socio-technical regimes stabilize existing trajectories in various ways: regulations and standards, sunk capital investments in technological infrastructures and competencies, adaptation of lifestyles to technical systems, and cognitive daily practices that blind engineers to technological developments outside their area of concentration (Geels and Schot 2007). They shape technological innovations (Nelson and Winter 1982; Rip and Kemp 1998). A socio-technical regime may host a range of innovative technological niches, e.g., big data analytics and context-aware computing as a set of technologies and their novel applications pertaining to ICT of various forms of pervasive computing for environmental sustainability, which generate innovations to challenge the status-quo. Such niches constitute areas in which space is provided for radical innovative experiments, which relate to technology innovation activities. Raven (2005, p. 48) defines a technological niche as "a loosely defined set of formal and informal rules for new technological practice, explored in societal experiments and protected by a relative small network of industries, users, researchers, policy makers and other involved actors." It forms the microlevel where drastic novelties emerge and are initially unstable socio-technical configurations; niche-innovations are developed by small networks of dedicated actors, hence their low performance (Geels and Schot 2007). One strand of work within social studies of new technologies centers on "innovative experiments in alternative, sustainable technological niches and draws lessons from the challenges they face in the context of a dominant, unsustainable technological regime" (Smith 2003, p. 128). Innovative technological strategic niches are seen as "nurturing socio-technical configurations, which grow and displace incumbent regime activities" (Berkhout et al. 2003, p. 9), thereby transforming socio-technical regimes. This occurs through such niches focusing on the tensions taking place in the prevailing regimes that emanate from shifting circumstances in the wider socio-technical landscape with respect to the diverse trends pertaining to environmental urban sustainability that challenge existing socio-technical regimes. However, it "remains to be seen if these changes will be…realized and maintained and sustainable technological niche activities will go mainstream… To realize a full potential of sustainable technologies depends on whether or the extent to which they will solve the bottlenecks and fiascos inherent in the existing technological regimes" (Bibri 2014, p. 38) in the context of smarter cities with respect to environmental sustainability. Furthermore, as environmentally sustainable niches, big data analytics and context-aware computing as a set of technologies could offer lessons for policymakers in the transition to smarter cities as an environmentally sustainable urban development approach. The construction of better policy forms draw on the experiences of those involved in technological innovation activities (see Willis et al. 2007). Big data analytics and context-aware computing as innovative technological niches can transform technological regimes through concentrating on tensions within them. It is the shifting circumstances in the wider socio-technical landscape that trigger these tensions, and where climate change policy, growing environmental awareness, and transitions to smart sustainable cities as new global trends challenge the extant (unsustainable) technological regimes, to draw on Gibbs (2009). In fact, big data analytics and context-aware computing as niche activities are breaking through to the mainstream due to their potential to solve the bottlenecks in the extant technological regime in terms of advancing different aspects of environmental sustainability, as discussed earlier.

There has been increasing academic and policy interest in recent years in the idea that long-term environmental problems entail fundamental transitions in socio-technical regimes for meeting demands for energy and other services (Kemp and Rotmans 2005), which builds on efforts to apply knowledge from empirical and theoretical analysis of past socio-technical transitions to governing transitions in technological, sectoral, regional, or national systems (Carlsson et al. 2002; Geels 2005; Loorbach 2007). Smith (2003, p. 131) suggests that "recommendations for radical shifts to sustainable technological regimes entail concomitantly radical changes to the socio-technical landscape of politics, institutions, the economy and social values". This implies that "the socio-technical landscape forms an exogenous environment beyond the direct influence of niche and regime actors (macro-economics, deep cultural patterns, macro-political developments). Changes at the landscape level usually take place slowly (decades)" (Geels and Schot 2007, p. 400). This is due to the nature, scale, complexity, and intricacy of the landscape, the overall socio-technical context, which comprises societal beliefs and values and worldviews as intangible dimensions, as well as material structures and mechanisms pertaining to various institutions and the functions of the economy and related marketplace dynamics as tangible aspects. This indicates the confines to smarter cities as an environmentally sustainable urban development approach. This is predicated on the assumption that while technological strategic niches are vital sources of innovation that may hold potential for providing solutions for tensions in the extant socio-technical regime, "the adaptation process is confined by structures within the existing, mainstream regime" (Smith 2006, p. 453).

In all, in the context of smarter cities, there are three separate levels that transition governance must work within: landscape, regime, and niche (Kemp and Loorbach 2003; Foxon et al. 2009), each with its own set of actors that interact in a variety of ways. These actors can be classified into governments, market based-actors, and civil society. The first category is associated with political mechanisms—governance arrangements—in the form of funding schemes, research management (regulation of public research institutes), innovation and technology policies, regulatory standards, market manipulations by the state, public-private collaborations and partnerships, and so on. In this respect, government or politics generate top-down pressure from regulation and policy and the use of market and other forms of incentives, while promoting, spurring, and stimulating the collective learning mechanisms by supporting technological innovation financially and providing access to the needed knowledge (Foxon et al. 2009; Rotmans et al. 2001). Market-based actors interact with industry leaders to generate technological innovative ideas and share best practices. Civil society, which involves citizens, users, consumers, communities, and non-governmental organizations, can provide pressure for change in the direction of technological innovation associated with environmental sustainability. Overall, while innovative technological strategic niches (big data analytics and context-aware computing as a set of technologies and their novel applications) alone remain inadequate to instigate environmental transformations in the context of smarter cities and this brings about a change at the landscape level pertaining to the urban system, the socio-political structures, practices, and beliefs underpinning this landscape also require a radical alteration, which is prone to failure due to the inherent complexity surrounding the forms of the behavioral patterns of interaction among urban actors. However, through the exploration at the niche level, the development of technological innovations for environmental sustainability is likely to be stimulated thanks to the collective learning mechanisms and dynamics enabled by the heterogeneity of smarter cities.

10.8 The Role of Political Action in Smarter Cities as a Techno-Urban Discourse and an Amalgam of Innovation Systems

10.8.1 On the Discursive Genesis of Smarter Cities

The discourse of smarter cities and its relation to environmental sustainability as described in the literature constructs them as being the defining context of ICT of various forms of pervasive computing for sustainability (see Bibri and Krogstie 2016a). The debate focusing on the untapped potential of ICT of various forms of pervasive computing for catalyzing and boosting environmentally sustainable development toward achieving the long-term goal of environmental sustainability (e.g., Bibri and Krogstie 2017a, b) relates to the academic discourse of ICT for sustainability. This discourse has given rise to several other discourses, including ICT for environmental sustainability (e.g., Fuchs 2005). The discourse of ICT of various forms of pervasive computing for urban sustainability (e.g., Bibri and Krogstie 2016a) has gained popularity after the prevalent ICT visions of UbiComp, AmI, the IoT, and SenComp have become deployable and achievable computing paradigms, manifested in new faces of cities instantiating their associated visions. Both ICT visions and various forms of smarter cities constitute academic discourses (see Chap. 2 for further details). And all those discourses metonymically represent the discourse of sustainable information society, a meta-discourse which regulates the techno-urban discourse of smarter cities. Sustainable information society denotes "a society in which new…ICT…and knowledge are used in order to advance a good-life for all individuals of current and future generations. This idea is conceived in a multidimensional way, identifying ecological, technological, economic, political, and cultural aspects and problems" (Fuchs 2005, p. 219). In the discourse of information society, ICT is socially constructed as a powerful enabler and driver for social transformation (e.g., ISTAG 2006) and environmental modernization (e.g., Bibri 2015b). Specifically, "the underlying belief of the information society discourse is that a total social transformation is envisioned or predicted, and that this transformation is a positive and progressive movement." (Bibri 2015b, p. 139) By the same token, at the core of ecological modernization as an academic and environmental discourse is an established view of the potential of technological innovations to bring about advanced solutions for environmental challenges and problems. Ecological modernization is concerned with the shifts in "the central institutions and core practices of modern society deemed necessary to solve, avoid, or mitigate the ecological crisis" (Bibri 2015b, p. 35). One of its key dimensions is technology and the transformation of society (Huber 1985), which entails that environmental problems could be addressed through the development and application of more advanced and sophisticated technologies (Murphy 2000). In all, the idea of smarter cities as an urban system of society refers to cities that use ICT of various forms of pervasive computing to improve the quality of life of citizens as well as the efficiency of urban operations and services, while ensuring that they meet the needs of present and future generations with respect to environmental, social, and economic aspects. And the focus in this chapter is on the environmental dimension of sustainability.

10.8.2 Political Mechanisms: Shaping the Discourse and Innovation System of Smarter Cities

Based on the above discussion, it is important to recognize the interplay between smarter cities, the defining context of ICT of various forms of pervasive computing for environmental sustainability, and other scales; as well as the links to political processes, e.g., regulatory policies and governance arrangements. Explicitly, political action is of critical importance to the emergence, insertion, functioning, and evolution of smarter cities as both a techno-urban discourse and an amalgam of innovation systems. Indeed, political practice is at the core of the theory of discourse (e.g., Foucault 1972) and the theoretical framework of innovation system (e.g., Rånge and Sandberg 2015; Chaminade and Edquist 2010; Kemp 1997; Kemp and Rotmans 2005) in terms of the shaping role of political mechanisms in the production and evolution of discourses and socio-technical systems governing technological innovations respectively. Recommendations for smarter cities as drastic techno-urban transformations, which entail a set of intertwined socio-technical systems and a cluster of interrelated discourses embedded in the wider socio-technical landscape, are unlikely to proceed without parallel political actions. The same goes for recommendations for ICT of various forms of pervasive computing for environmental sustainability as drastic shifts to sustainable technological regimes, which “entail concomitantly radical changes to the socio-technical landscape of politics, institutions, the economy, and social values” (Smith 2003, p. 131), to reiterate. From a discursive perspective, political processes are at the heart of material mechanisms and practices in terms of translating the visions of smarter cities into concrete projects and strategies and their institutionalization in urban structures and practices (see Sum 2006). And from an innovation system perspective, political processes represent the set-up under which dynamic networks of urban actors and entities can interact within diverse industrial sectors in the development, diffusion, and utilization of knowledge and technology pertaining to sustainable urban development and its smart dimension.

Political action shapes the emergence, insertion, functioning, and evolution of smarter cities, to reiterate. This urban transformation has a quite strong governmental and policy support, particularly within ecologically and technologically advanced societies. It figures in many policy documents and agenda as well as political statements and argumentations, in addition to being used by many institutions (e.g., industry, universities, research institutes, etc.). Policymakers explicitly refer to such meta-discourses as global sustainability, urbanization, and knowledge-based society when trying to legitimize smarter city politics. It is not an element closed in the “ivory tower” of research community, but it is influenced by the macro-political practices in connection with the environmentally sustainable development and ICT innovation. This is anchored in the premise that drastic urban shifts such as smarter cities are unlikely to proceed without parallel political action, to reiterate. As a corollary of its dynamic interaction with new discourses, politics forces their emergence, insertion, functioning, and evolution (see Foucault 1972). Below we outline the key facets of the operations that link the creation and evolution of the discourse of smarter cities and political action.

The first mechanism utilized by political action that promotes and makes function the discourse of smarter cities is the creation of regulatory and policy instrument and incentives. A driver for smarter cities is to comply with environmental transformation emerging as an outcome of government regulations and legislations. These hard structural factors have an important role to play in shaping the way smarter city practices are performed and maintained. However, since appropriate policy and regulatory frameworks are necessary to achieve urban change and alter urban development behavior, governments need to construct the most cost-effective approaches in this regard. Hence, new policy designs necessitate in-depth cost-benefit analyses to promote smarter cities.

The second mechanism is associated with assigning scholarly roles and/or institutional positions to particular organizations, thereby authorizing them and legitimizing their actions as to conducting R&D activities pertaining to, for example, big data analytics and context-aware computing with regard to innovation pertaining to various forms of pervasive computing, contributing to technology and innovation policy formation, and constructing new techno-urban visions, and so on. This mechanism relates to "regimes of truth" in the sense that ecologically and technologically advanced societies have, drawing on Foucault (1972), their "general politics of truth, i.e. the historically specific mechanisms which both produce discourses and make them function as true in particular times and places, as well as enable one to distinguish the status of actors that are in charge with saying and advancing what counts as true knowledge…and thus have the legitimacy to hold or create new discourses. These regimes of truth are supported by discursive formations, the regularities that produce discourses [sciences, disciplines, rationalities, etc.], and made true through discursive practices [e.g. scientific reports and academic publications], through which social and cultural reproduction and change take place." (Bibri 2015b, p. 83).

Government involvement in smarter city projects and initiatives is a third mechanism by which political action forces the emergence and insertion of smarter cities. This is manifested in such actions as funding ICT of various forms of pervasive computing innovations for environmental sustainability, providing positive incentives to urban markets, encouraging utilization of data-centric and context-aware applications that improve environmental sustainability, advocating adoption of environmentally friendly services, greening environmentally-unfriendly urban sectors, and stimulating debates over the need to smartening up cities and incorporating the goal of environmentally sustainable development into smarter cities. In the context of smarter cities, the role of policymaking is seen in forums and symposiums, in national programs, and in local environmental programs and comprehensive plans (see Höjer and Wangel 2015). Thus, governments direct their efforts toward creating an enabling environment conducive to large-scale urban innovations that contribute to the global environmental transformation of the city.

Lastly, political action contributes to mainstreaming smarter cities by accumulating and preserving the related body of knowledge, as well as disseminating and imparting their principles. This is typically carried out inside centers for research and innovation and higher educational institutions, and in specific research areas pertaining to urban analytics, smart urban planning, urban informatics, applied urban science, and urban computing. In the face of it, the interest in smarter cities has started to spill out into the wider sustainable urban planning and development education, and initiatives intended specifically to support and foster smart sustainable urban development are burgeoning, as evidenced by many schools in a wide and large number of universities and research institutions across the world introducing new modules and courses (e.g., big data analytics, urban simulation models, smart urban metabolism, smart urbanism, smart energy, smart transport, smart environment) into sustainable urban planning and development, especially within ecologically and technologically advanced nations (see Bibri and Krogstie 2016a).

It is of crucial importance to invest in research activities and education programs focused on smart technologies for environmental sustainability. In this context, the emergence of smarter cities should be approached through what Ciborra (2004) terms the lens of "hospitality", a lens through which we can alien affordances of smarter cities and embrace and implement their advantages and better understand their disadvantages. It is in research institutions and universities where this hospitality can best be achieved, and which can use and explore smarter cities as laboratories of innovation. These research and educational entities are well positioned to readily host the emergence of smarter cities, and seek innovative solutions and sophisticated approaches of relevance to the challenge of environmental sustainability with regard to developing new metrics for measuring and new methods for assessing the urban progress toward achieving the goal of environmentally sustainable development in the context of smarter cities. Another strategic value of investing in research and education lies in training and educating a new generation of interdisciplinary researchers, scholars, and practitioners within the domain of environmental urban sustainability, as well as in gaining new knowledge to explore opportunities of using and applying advanced ICT in solving real-world problems in the realm of smarter cities.

The shaping role of political action in the development and evolution of smarter cities is also of focus in national innovation system. This implies that such cities have to conform to government regulations and policies on the national level. This relates to the first political mechanism mentioned above. A national innovation system can be described as a set of distinct institutions whose interactions and relationships lead to, through incentive structures, competencies, collective learning, and networks, the development, diffusion, and utilization of knowledge and technology, and which provide frameworks that enable governments to formulate and implement policies to influence innovation activities (e.g., Metcalfe 1995; Edquist 2011), e.g., big data analytics and context-aware computing technologies and their novel applications. In theory, the evolutionary patterns underlying national systems trigger or instigate innovation processes, as they generate interactive dynamics among organizations (Bergek et al. 2010; Edquist 2011; Freeman 1995; Lundvall 1992; Nelson 1993), which pertain to changes in technologies, institutions, and corporate strategies. In a nutshell, it is the political history that shapes the industrial structure of most, if not all, innovation systems. Accordingly, regulatory, policy, and institutional frameworks are regarded as means to influence interactive dynamics among organizations, such as shifting technological innovative focus from unsustainable to sustainable production and consumption, sustainable energy use, and sustainable services (e.g., Bergh 2007; Chaminade and Edquist 2010; Kemp 1997; Kemp and Rotmans 2005). They therefore constitute driving forces or incentive structures of transformation to new technologies (e.g., UbiComp, AmI, the IoT, and SenComp) for environmental sustainability and related institutional systems in the context of smarter cities. Institutional frameworks are necessary to alter relations and linkages among innovative actors, and thus play an important role in shaping the way these technologies are diffused and evolve. Institutional changes are expected to be "behind most, or at least many, of the technological changes that reduce environmentally unfriendly effects… Institutions created and modified within the framework of the political…system are typically formulated in a way that distinguishes between public and private ownership and therefore also how public organizations are managed versus how private corporations are handled" (Rånge and Sandberg 2015, p. 4). In all, entailing multiple tools, methods, and actors, the intervention of the state in the pursuit of environmental urban sustainability through political action to ensure that supportive institutional structures are in place is potentially effective.

There are diverse political mechanisms used by political action to enable and spur smarter cities and what they entail in terms of new technologies and their novel applications. They entail such governance arrangements as funding schemes, research management, innovation and technology policies, regulatory standards, market manipulations by the state, public–private partnerships, and so on (Bibri 2015b), to reiterate. Arguably, these mechanisms influence in different ways the functionality of ICT of various forms of pervasive computing for environmental urban sustainability and thus smarter cities as a system of innovation systems, and the degree of the influence is contingent upon such societal factors as the relation to established technologies, political culture and agenda, policy designs, institutional behavior, industrial leadership, and economic conditions. In light of this, smarter cities should not be conceived of as "isolated islands", or seen as natural layers of scientific organization (see Bibri 2015b). Rather, they represent social constructions whereby seamless webs of societal factors and actors shape the emergence, development, uptake, and evolution of the underlying ICT of various forms of pervasive computing the for environmental sustainability. The related new technologies constitute innovative technological strategic niches within the evolving sustainable technological regimes embedded in the wider socio-technical landscape of ecologically and technologically advanced societies (see, e.g., Rip and Kemp 1998; Smith 2003; Geels 2005), regions, or cities, as discussed above.

Similarly, smarter cities, the overall setting for ICT of various forms of pervasive computing for environmental sustainability, affect the societal structures that surround them. They tend to engender changes in socio-political institutions and cultural shifts associated with the link between ICT innovation and environmental sustainability, as well as bring about qualitative changes in urban industry strategies, structures, and operations with respect to smart urban projects and comprehensive plans supportive of environmental sustainability. Challenges to technological regimes emanate from, at the microlevel, the development of a wide range of sustainable technologies and their smart applications and services, and their implementation in urban domains and strategies to meet the needs of urbanites. ICT of various forms of pervasive computing for environmental urban sustainability as innovative technological strategic niches are "reconfiguring the wider socio-technical landscape [and its technological regimes] and providing insights for policymakers into pathways for the transformation of institutions and…urban practices to mitigate…environmental crisis.” (Bibri 2014, pp. 37–38) Likewise, smarter cities “will be the boost to new forms of policy analysis and planning in the information age, and the greatest impacts of new technologies will be on the way we organize ourselves in cities and the way we plan this organization.” (Batty et al. 2012, p. 483) This will continue to evolve as smart sustainable urban development practices and ICT innovations for environmental sustainability get further adopted and implemented, and their influence keep on gathering momentum toward reshaping unsustainable technological regimes in the realm of smarter cities.

10.8.3 Discursive-Material Dialectics of Smarter Cities

Macro processes of political regulation and policy are salient factors in the discursive-material dialectics of smarter cities as an urban transformation. With being a hegemonic semantic order, smarter cities as techno-urban visions have been constructed (see, e.g., Jessop 2004; Fairclough 2005). That is to say, they have resonated with material mechanisms and practices. Constituting techno-urban objects and their related subjects with specific material and ideal interests (discursive constructions), smarter cities as techno-urban imaginaries have a pivotal role alongside material mechanisms and practices in reproducing and/or transforming urban domination (see Sum 2006). Smarter cities as representations have been discursively construed in different spatial contexts (cities within technologically advanced nations) and reproduced materially through institutional and organizational apparatuses and their techniques, actors, and practices (see Jessop 2004). This material reproduction entails the translation of the underlying techno-urban visions into hegemonic techno-urban strategies, projects, and initiatives, as well as their institutionalization in city structures and urban practices. As regards to the construal of smarter cities, Jessop (2004, p. 164) asserts that the relative success of discursive construals, which “can be durably constructed materially”, “depends on how… [it] and any attempts at construction correspond to the properties of the materials…used to construct social reality.” This supports the argument about the discursive-material dialectics and the prominence of discursivity and materiality to an adequate account of the reconstruction of smart urban transformation. Specifically, focusing on how politics in the context of smarter cities is done in a dialectic interplay between “*discursive selectivity* (discursive chains, identities, and performance) and *material selectivity* (the privileging of certain sites of discourse and strategies of strategic actors and their mode of calculation about their ‘objective interests’, and the recursive selection of these strategies)” (Sum 2006, p. 8) in different spatial contexts is crucial to understand why the new discourse of smarter cities has been translated into concrete projects and strategies and, thus, policy orientation has been legitimated with references to it, to draw on Bibri (2015b). In all, there is a mutual dependence between semiosis and the material world, a dialectic interplay in which smarter cities is constructed as an urban reality from an ontological standpoint. Semiosis refers to "the intersubjective production of meaning" and can be viewed as an umbrella concept for discourse and language (Jessop 2004, p. 161).

The dialectic of discursivity and materiality is in turn crucial to the social construction of smarter cities. This involves developing, institutionalizing, and conventionalizing this techno-urban phenomenon by the information society (specifically technologically advanced societies) through social constructs or cultural frames (see Chap. 2 for further discussion). These constructs or frames represent models of the urban world that are created, shared, and reified through language in the form of scientific documents and academic publications. Social constructionism posits that people rationalize their experiences through models and language (Leeds-Hurwitz 2009), concrete language use. Further, social constructs or cultural frames are produced by and depend on contingent aspects of people as social selves through social practices which form objects that an array of previous and current academic discourses on cities and urban development talk about. Accordingly, the constitution and reconstitution of urban life occur through text production and consumption processes. This is predicated on the assumption that social and cultural change (production and reproduction) occurs through discursive practices. In light of this, recent years have witnessed a proliferation of scholarly writings on the growing role of ICT of various forms of pervasive computing in advancing environmental sustainability, a form of semiosis which has generated the current discursive constructions of ICT of various forms of pervasive computing for environmental sustainability in the defining context of smarter cities. The related magnitude and diversity of academic research has in turn given rise to smarter cities as a holistic approach into urban development. This body of work continues to flourish and is consequently instigating drastic urban transformations in terms of the way the city functions and can be developed and planned in line with the vision of environmental sustainability. This is being fueled by the academic debates on sustainability science (e.g., Clark and Dickson 2003; Clark 2007) and its technology orientation in relation to evaluating and mitigating the unintended consequences of anthropogenic activities "on planetary systems and on societies across the globe and into the future" (Kieffer et al. 2003), in general, and its connection with ICT of various forms of pervasive computing in the context of urban planning and development, in particular. Sustaining the momentum is also explained by the resonance of this new intellectual trend with the practices of local city governments, landscape architects, urban planners, infrastructure companies, research institutions, sustainable development institutes, policymakers, and ICT industry consortia. These corroborating aspects pertain to environmentally sustainable urban development studies, projects, initiatives, strategies, and policies taking place in technologically advanced societies across the globe.

10.9 Conclusions

ICT of various forms of pervasive computing is giving rise to new faces of cities, which are characterized with augmented smartness and what this entail in terms of computer and information intelligence directed for advancing different aspects of environmental sustainability. The overall aim of this chapter was manifold. First, this chapter reviewed the key deficiencies, misunderstandings, fallacies, and challenges associated with smart and smarter cities with respect to environmental sustainability. Smart and smarter cities still focus primarily on the advancement of ICT of various forms of pervasive computing and its potential only in terms of novel applications and services and their role in improving the quality of life of citizens and enhancing economic productivity and efficiency, and fall short in considering environmental concerns, notwithstanding the untapped potential of emerging and future ICT in accelerating and advancing environmental sustainability in the context of smart and smarter cities. Indeed, both current smart cities and emerging smarter cities raise several issues—when it comes to their development and implementation as to their concrete contribution to and explicit incorporation of the fundamental goal of environmentally sustainable development. Therefore, it is timely and necessary to guide and direct the transition of smart cities to smarter cities with a rather clear strategy for aligning the development and innovation of ICT of various forms of pervasive computing with the goal of environmentally sustainable development, or linking emerging and future technological progress with the vision of environmental sustainability.

Second, this chapter identified the significant risks that smarter cities pose to environmental sustainability by means of relying on ICT of various forms of pervasive computing, including GHG emissions, intensive energy consumption, toxic waste, and resource depletion. Such risks are expected to escalate during the transition of smart cities to smarter cities, as the ubiquity presence and massive use of ICT is associated with adverse effects on the environment. In fact, one of the significant challenges for smarter cities is to develop and implement assessment methods and practices that take a holistic approach into evaluating the implications of ICT solutions on the environment (e.g., Bibri and Krogstie 2016a, 2017a). Without such methods and practices, smarter cities risk becoming an empty signifier or without validated content, and consequently, will serve nothing but economic and political ends. Therefore, the value-neutrality of ICT of various forms of pervasive computing and the ethics of its imperative are to be questioned and challenged (Bibri and Krogstie 2016a). The point is that smarter cities need, and could be, reoriented in a more environmentally sustainable direction, as it can not—as currently envisioned and practiced—solve the complex environmental problems placed on the agenda of smart sustainable cities of the future as a holistic approach to urban development (Bibri and Krogstie 2016a). In this regard, there are different measures that can be taken to mitigate the diverse environmental risks posed by ICT of various forms of pervasive computing, including design for the environment, sustainable design/eco-design approach, de-carbonization strategy, planning instruments, innovation policies, and regulatory frameworks. Under current economic, social, political, and physical structures of smart cities and emerging smarter cities, ICT of various forms of pervasive computing remains filled with rebound and systemic effects as unintended consequences, coupled with direct and indirect effects. But it can look very different if those measures are taken into account with regard to analyzing the environmental benefits and costs of ICT design, development, application, and use in the context of smarter cities. In all, political decisions made with regard to directing ICT of various forms of pervasive computing for environmentally sustainable development, taking into account the interactions between the two fields in the context of smarter cities, must be based on prospective analysis of the positive and negative effects of ICT. This should consider the dynamics both of the development and innovation of ICT of various forms of computing as well as its impacts on the systems of smarter cities and its interactions with the environment. Otherwise, such analysis would be almost useless and meaningless.

Third, this chapter aimed to substantiate the potential smarter cities hold in accelerating and advancing environmental sustainability on the basis of ICT of various forms of pervasive computing. Smarter cities are still at the early stage of their development and thus could, if planned strategically, do a lot more in this regard, including the mitigation of environmental risks posed by ICT itself (GHG emissions, intensive energy consumption, toxic waste, resource depletion, etc.), if linked to the goal of environmentally sustainable development before they get widely adopted and deployed in the years ahead. Significant opportunities exist for UbiComp, AmI, the IoT, and SenComp—and hence big data analytics and context-aware computing—in relation to advancing the model of smarter cities in terms of the environmental dimension of sustainability, as the range of urban application areas that utilize these advanced technologies and their novel applications in connection with environmental sustainability is potentially huge. In other words, ICT of various forms of pervasive computing ushers in automation and intelligence in nearly all urban domains.

Fourth, this chapter intended to probe both the ways in which the transition of smart cities to smarter cities (with environmental sustainability in mind) can be managed or governed at the macro level as well as the role of politics and policy in the creation and evolution of smarter cities. This entailed drawing on different theoretical perspectives from socio-technical studies, innovation studies, and discursive studies, most notably transition governance; technological and national innovation systems; and the link between political practice and the emergence, insertion, and functioning of new discourses. The extent to which smarter cities could be achieved as envisioned with respect to environmental sustainability can be valuably explored based on research within transition governance. There are three separate levels that transition governance must work within in this regard: landscape, regime, and niche. Transition governance emphasizes the role and contribution of innovative technological strategic niches in the process of transitioning from smart cities to smarter cities with environmental sustainability in mind. Such niches (in this context big data analytics and context-aware computing as a set of advanced technologies and their novel applications) are seen as having a role in nurturing socio-technical configurations. As environmentally sustainable niches, they could offer lessons for policy and decision-makers as key pillars of socio-technical landscape to instigate the transition to smarter cities. They could accordingly transform technological regimes. The underlying assumption is that radical shifts to technological regimes necessitate concomitantly radical changes to the wider socio-technical landscape, which is an exogenous setting beyond the influence of strategic niche and technological regime actors.

Furthermore, political action has a shaping role in the emergence, insertion, and functioning of smarter cities as a techno-urban discourse and an amalgam of innovation systems. It involves different mechanisms as operations that link the creation and evolution of smarter cities and politics. Hence, smarter cities are not an element closed in the "ivory tower" of research community, but rather they are influenced by the macro-political practices in connection with environmentally sustainable development and ICT development and innovation. Foucault (1991) posits that while political practice does not alter the meaning and form of discourses, it does shape the conditions of their appearance, assimilation, and functioning. Accordingly, drastic turban shifts such as smarter cities are unlikely to proceed without parallel political action. In more detail, it is important not to conceive of smarter cities as "isolated islands", and thus to recognize the interplay between such cities and other scales, as well as the links to political and regulatory processes on a macro level. Macro processes of political regulation and policy remain determining factors in the discursive-material dialectics of smarter cities as an urban transformation. Worth noting is that the different mechanisms currently being used by political action to promote, develop, and expand smarter cities across the globe point toward changes to the landscape of institutions, politics, and policy pertaining to ecologically and technologically advanced nations. These social rules systems governing smarter cities are interacting with shifts in sustainable technological regimes engendered by the actions and networks of actors within these institutions and governmental and policy bodies. This is consistent with the theoretical perspective on new discourses reshaping social structures due to their power implications.

Fifth, this chapter endeavored to reflect on what it means for smart cities to move behind their foundational visions as they transition to smarter cities and embrace environmental sustainability as an important trend increasingly gaining prominence in urban development as a result of the unprecedented urbanization of the world. It is timely to re-interpret the role of smart cities in the background of two decades or so of research and a decade or so of practical implementation. The visions of smart cities have played an important role in establishing the field of smart urban development, but it is now time for these visions to move beyond their prevailing assumptions pertaining to the sole, core focus on ICT and its advancement and potential for efficiency. The main motivation for challenging and questioning the way such visions have been evolving is to search for alternative research directions that by taking environmental sustainability into account can be more effective in reshaping smarter cities and delivering the essence of the underlying visions. This entails activating the idea that the integration of ICT into the very fabric of the city may well have a profound and positive impact on the environment. This epitome involves abandoning some of the currently prevailing approaches, claims, and assumptions underlying smart cities. Overall, smarter cities provide a more holistic view of smart urban development and may represent important contributions for accelerating and advancing environmental sustainability.

All in all, we argue that ICT of various forms of pervasive computing will provide immense opportunities for smarter cities to build urban environments conducive to accelerating and advancing environmental sustainability by providing innovative solutions and sophisticated approaches, as well as by employing and implementing cutting-edge technologies and their novel data-centric and context-aware applications that integrate and harness urban systems and facilitate collaboration and coordination among urban domains.

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Chapter 11
Approaches to Futures Studies: A Scholarly and Planning Approach to Strategic Smart Sustainable City Development

Abstract Backcasting as a scholarly and planning approach is increasingly used in futures studies in fields related to urban sustainability as an alternative to traditional planning approaches and a formal element of future strategic initiatives. It is viewed as a natural step in operationalizing sustainable development within different societal spheres. As a holistic urban development strategy, smart sustainable cities represent a manifestation of sustainable development as a process of change and a strategic approach to achieving the long-term goals of sustainability. Achieving smart sustainable cities represents an instance of urban sustainability, a concept that refers to a desired state in which a city strives to retain the balance of socio-ecological system through sustainable development as a desired trajectory. This long-term goal requires fostering linkages between scientific and social research, technological innovations, institutional practices, and policy design and planning in relevance to urban sustainability. It also requires a long-term vision, a transdisciplinary approach, and a system-oriented perspective on addressing environmental, economic, and social issues. These requirements are at the core of backcasting as an approach to futures studies. As there are a number of backcasting approaches used in different domains, and the backcasting framework is adaptive and contextual in nature, it is deemed highly relevant and useful to devise a scholarly and planning approach to strategic smart sustainable city development. This chapter has a fourfold purpose. It aims to (1) provide a comparative account of the most commonly applied approaches in futures studies dealing with technology and sustainability (forecasting and backcasting); (2) to review the existing backcasting methodologies and discuss the relevance of their use in terms of their steps and guiding questions in analyzing strategic smart sustainable city development as an area that is at the intersection of city development, sustainable development, and technology development; (3) to synthesize a backcasting approach based on the outcome of the review and discussion, and (4) to examine backcasting as a scholarly methodology and planning approach by looking at its use in the Gothenburg 2050 Project and an ongoing Ph.D. project, as well as to use these cases to illustrate the core and relevance of the synthesized approach. Backcasting is a special kind of scenario methodology to develop future models for smart sustainable city as a planning tool for urban sustainability. Goal-oriented backcasting approaches declare long-range targets that lie quite far in

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the future. Visionary images of a long-term future can stimulate an accelerated movement toward achieving the goals of urban sustainability. The backcasting approach is found to be well suited for long-term urban sustainability solutions due to its normative, goal-oriented, and problem-solving character. Also, it is particularly useful when: dealing with complex problems and transitions, the current trends are part of the problem, and different directions of development can be allowed given the wide scope and long time horizon considered. A number of recent futures studies using backcasting have underlined the efficacy of this scholarly and planning approach in terms of indicating policy pathway for sustainability transitions and thus supporting policymakers and facilitating and guiding their actions. The synthesized scholarly and planning approach serves to help researchers and scholars in analyzing strategic smart sustainable city development to assist planners, policymakers, and decision-makers in their endeavor to implement smart sustainable cities.

Keywords Smart sustainable cities · Sustainability · Sustainable development
Backcasting · Forecasting · Futures studies · Strategic planning
Strategic smart sustainable city development · Scholarly and planning approach

11.1 Introduction

The central role of cities in sustainable development is clearly reflected in the Sustainable Development Goals (SGDs) of the United Nations (2015c) 2030 Agenda for Sustainable Development, which is about making cities resilient and sustainable (SDG Goal 11). The defining role of cities in sustainable local and global development is well documented (European Commission 2011; United Nations 2015c). As the engines of economic growth, cities are the world's major consumers of energy resources and significant contributors to GHG emissions. They consume 67% of the global energy demand and generate up to 70% of the harmful GHG emissions (e.g., Creutzig et al. 2015). Thus, they represent key generators of environmental pollutants and main hotspots of vulnerability to climatic hazards and natural disasters resulting from climate change, as well as complex challenges pertaining to social inequality and disparity. This is due to the density of urban population and the intensity of economic and social activities, coupled with the inefficiency of the built environment (land use, urban design, and transportation).

Contemporary cities have increasingly gained a central role in applying the discourse of sustainable development and ecological modernization. They are seen as the most important arena for sustainability transitions because they constitute key sites of economic, environmental, and social dynamism and innovation making significant contributions to sustainable transformations and thus social change and cultural advancement. As such, they offer ideal testing grounds for new solutions spanning diverse sectors. As they are essentially places where new ideas are created, tested, and advanced, many sustainable urban development frameworks and approaches reference the role of ICT in advancing the goals of sustainable development (e.g., Angelidou et al. 2017; Angelidou and Psaltoglou 2017; Al Nuaimi et al. 2015; Bibri 2018; Taghavi et al. 2014). For example, the UN’s 2030 Agenda for Sustainable Development sees ICT as a means to promote economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (United Nations 2015b, c). The tremendous and multifaceted potential of the smart city approach has been under investigation by the United Nations (2015a), through their study on “Big Data and the 2030 Agenda for Sustainable Development.” ICT constitutes a promising approach to decoupling the well-being and health of the city and the quality of life of citizens from the energy and material consumption and concomitant environmental risks associated with urban operations, functions, services, and designs. Sustainable development is a continuously unfolding but strategic pathway for change centered on bringing environmental, economic, and social considerations to the core of our understanding of human, social, and technological development. Potentially, this involves the reconfiguration of economic and societal activities within prominent sectors based on an all-embracing understanding of the problems facing society. This is necessary for making all-inclusive decisions and taking well-informed actions for the long-term benefit of society. This implies in the context of future cities the integration of environmental information with physical, economic, social, and technological dimensions in decision-making and planning processes.

In light of the above, recent research endeavors have recently started to focus on amalgamating sustainable cities and smart cities as urban development strategies in an attempt to achieve the required level of sustainability with respect to urban operations, functions, services, designs, and policies under what is labeled “smart sustainable cities of the future”. Especially, smart cities have been criticized for their lack of explicitly incorporating the goals of sustainable development (e.g., Bibri 2018; Höjer and Wangel 2015; Kramers et al. 2014), and sustainable cities for facing difficulties in translating sustainability into the built environment and for evaluating the extent to which different sustainable urban forms contribute to the goals of sustainable development (Bibri and Krogstie 2017b; Hofstad 2012; Jabareen 2006; Kärrholm 2011; Williams 2009). Adding to these is the weak or lack of connection between the two urban development strategies, despite the proven role of ICT in supporting cities in their transition toward the needed sustainable development (e.g., Ahvenniemi et al. 2017; Bifulco et al. 2016; Kramers et al. 2014). On this note, Angelidou et al. (2017) conclude that the smart city and sustainable city landscapes are extremely fragmented both on the policy and the technical levels, and there is a host of unexplored opportunities toward smart sustainable city development. In addition, both existing sustainable city models and smart city approaches pose special conundrums, raise several issues, and face significant challenges—when it comes to their development and implementation in the context of sustainability. Such models are associated with limitations, uncertainties, and fallacies, and such approaches with deficiencies and misunderstandings with regard to the contribution the goals of sustainable development (see Bibri and Krogstie 2017a for an extensive literature review). The basic idea of smart sustainable cities of the future is that this holistic urban development approach seeks to explicitly bring together sustainable cities and smart cities as urban endeavors in ways that address and overcome the key shortcomings of both classes of cities in terms of their contribution to the goals of sustainable development. This can be accomplished by merging and leveraging what each class has to offer for sustainability in terms of ICT of pervasive computing and its novel applications as an enabling technology for smart cities and the design concepts and planning principles guiding sustainable urban forms, with the sheer purpose of advancing sustainability in an increasingly technologized, computerized, and urbanized world (Bibri 2018). In light of this, there can be a diversity among programs and initiatives projects considered to be smart sustainable cities. In this sense, it can be argued that, it is better to think of the smart sustainable city as an objective which there will be multiple ways to achieve, as well as diverse planning approaches into planning such city. Backcasting as a scholarly methodology is well suited to this multifaceted kind of planning process (see Phdungsilp 2011).

Smart sustainable cities represent a manifestation of sustainable urban development as a process of change and a strategic approach to achieving the long-term goals of sustainability. Accordingly, such strategy is intended to achieve the required level of sustainability as to operational functioning, planning, and governance with support of ICT of pervasive computing as a set of advanced technologies and their novel applications pertaining to big data analytics, context-aware computing, and other recent computing waves. Achieving the state of smart sustainable cities represents an instance of urban sustainability, a concept that refers to a desired (normative) state in which a city strives to retain a balance of socio-ecological systems through the strategic process of sustainable development as a desired trajectory. Urban sustainability is cast in terms of four dimensions: physical, environment, social, and economic, which should all be enhanced over the long run—given their interdependence, synergy, and equal importance. To achieve this long-term goal requires a planning framework for strategic smart sustainable city development that facilitates and contributes to the design, development, implementation, evaluation, and improvement of urban systems, including practical interventions for coordinating, integrating, and coupling urban domains, using cutting-edge technologies. This strategic endeavor should focus on replenishing resources, lowering energy use, lessening pollution and waste levels, while improving social justice, equity, stability, and safety. Accordingly, it can best be pursued through backcasting as a strategic planning approach due to its appropriateness for addressing sustainability issues (see, e.g., Carlsson-Kanyama et al. 2003; Dreborg 1996; Holmberg and Robèrt 2000; Phdungsilp 2011).

Importantly, the strategic sustainable urban development approach to achieving the long-term goals of urban sustainability should aim at fostering linkages between scientific and social research, technological innovations, institutional and organizational practices, and policy design and planning in relevance to sustainability. Achieving smart sustainable cities requires a long-term vision, an interdisciplinary and transdisciplinary approach, and a system-oriented perspective on addressing environmental, economic, and social issues. All these requirements are at the core of futures studies on urban sustainability using backcasting approaches (e.g., Carlsson-Kanyama et al. 2003; Miola 2008; Phdungsilp 2011). Any backcasting approach should accordingly be grounded in theoretical, disciplinary, and discursive foundations (see Bibri 2018 for a multidimensional framework for smart sustainable city development), supported by an in-depth analysis of cases involving projects, programs, strategies, and successful practices as necessary for directing actors toward urban sustainability and analyzing its impacts. Backcasting is a process of starting from a desirable (sustainable) future as a vision of success, then looking back to today to identify the most strategic steps necessary for achieving that specified future. In this regard, achieving smart sustainable cities as a future state can be viewed as a vision of success since the purpose of the planning and development process is to attain the long-term goals of sustainability. The goal of smart sustainable cities requires a paradigm shift in city governments, organizations, and citizens driven by responsible environmental management, technological innovations, and behavioral change. These are usually reflected in the questions guiding most of the backcasting approaches applied in the domain of urban sustainability.

In addition, the problems that both smart cities and sustainable cities face today will increase in the future with much greater compounding affects. Consequently, policy actions for developing smart sustainable cities of the future ought to be applied, tested, transformed, disseminated, and adapted to help solve those problems. Smart sustainable cities require long-term strategic planning to overcome their particular challenges. An appropriate response to smart sustainable city development involves the analysis of several factors, including past, present, and future situations; long-term visions; formulation, implementation, and follow-up; transfer and deployment of technologies; building and enhancement of human and social capacity; and regulatory policies. These factors are intertwined and thus cannot be isolated from each other in all kinds of urban sustainability endeavors, which indeed require a system-oriented perspective to addressing environmental, economic and social issues. Futures studies offer promising approaches to building smart sustainable city foresight, especially in the situation where the problem is complex and major change is needed. With this in regard, this chapter examines the futures studies approaches that can be used for smart sustainable city development. And its focus is on the backcasting approaches as planning tools due to their suitability and usefulness to urban sustainability. Envisioning smart sustainable cities as future human settlements has an obvious normative side: what futures are desired? Backcasting the preferred vision of the future has an analytical side: how can we attain this desirable future?

This chapter has a fourfold purpose. It aims to (1) provide a comparative account of the most commonly applied approaches in futures studies dealing with technology and sustainability (forecasting and backcasting); (2) to review the existing backcasting methodologies and discuss the relevance of their use in terms of their steps and guiding questions in analyzing strategic smart sustainable city development as an area that is at the intersection of city development, sustainable development, and technology development; (3) to synthesize a backcasting approach based on the outcome of the review and discussion, and (4) to examine backcasting as a scholarly methodology and planning approach by looking at its use in the Gothenburg 2050 Project and an ongoing Ph.D. project, as well as to use these cases to illustrate the core and relevance of the synthesized approach. Backcasting is a special kind of scenario methodology to develop future models for smart sustainable city as a planning tool for urban sustainability. Goal-oriented backcasting approaches declare long-range targets that lie quite far in the future. Visionary images of a long-term future can stimulate an accelerated movement toward achieving the goals of urban sustainability. The motivation for this chapter is to provide guidelines and tools for the development of smart sustainable cities of the future as a vision of success, as well as to stimulate focused research opportunities, mobilization of resources, and alignment of stakeholders in the same direction. It is moreover to bring scholars and practitioners on common ground to bring enhanced practices and advanced technologies to bear in an effort to strategically assess, improve, and sustain the contribution of smart sustainable cities to the goals of sustainable development within ecologically and technologically advanced nations.

This chapter is organized as follows. Section 11.2 introduces, describes, and discusses relevant theoretical constructs, namely strategic smart sustainable urban planning and strategic smart sustainable urban development. Section 11.3 provides an account of futures studies, covering dimensions, aims, types, and approaches, with a focus on sustainability issues. Section 11.4 reviews the existing backcasting methodologies and discusses the relevance of their use in terms of their steps and guiding questions in analyzing strategic smart sustainable city development as a scholarly area that integrates city development, sustainable development, and technology development. Section 11.5 synthesizes a backcasting framework as a scholarly and planning approach to strategic smart sustainable city development based on the outcome of the review and discussion. Backcasting is examined, in Sect. 11.6, by looking at its use in the Gothenburg 2050 Project and an ongoing Ph. D. project. A discussion of backcasting as a useful tool for achieving urban sustainability is the object of Sect. 11.7. In it, the emphasis is on the shaping role of political action in sustainability transitions as part of societal planning. Section 11.8 discusses systems thinking and backcasting in relation to smart sustainable cities. The chapter ends, in Sect. 11.9, with concluding remarks and some reflections.

11.2 Theoretical Background

11.2.1 Strategic Smart Sustainable Urban Planning

Institutionalized in many industrialized nations since the late nineteenth century, urban planning (also referred to as city planning and urban development) is a governmental function in most countries worldwide. It is practiced on neighborhood, district, city, metropolitan, regional, and national scales with land use, environmental, transport, local, metropolitan, and regional planning representing more specialized foci. Accordingly, urban planning is a political and technical process concerned with the development and use of land, the protection and use of the environment, the design of the urban environment, and public administration and welfare. Several notable books (e.g., Jacobs 1961; Lynch 1981; McHarg 1995; Mumford 1961; Wheeler and Beatley 2010) have been written on the subject of urban planning (and development). They have approached it from a variety of perspectives, often combined, including physical, spatial, social, cultural, political, economic, and ecological. Urban planning is the process of guiding and directing the use and development of land, urban environment, and natural environment, as well as ecosystem and human services—in ways that ensure effective utilization of natural resources, intelligent management of infrastructures and facilities, efficient operations and services, optimal economic development, and high quality of life and well-being. In more detail, urban planning involves drawing up, designing, evaluating, and forecasting an organized, coordinated, and standardized physical arrangement and infrastructural system of a city and the associated processes, functions, and services, i.e., built form (buildings, streets, residential and commercial areas, facilities, parks, etc.), urban infrastructure (transportation, water supply, communication systems, distribution networks, etc.), ecosystem services (energy, raw material, air, food, etc.), human services (public services, social services, cultural facilities, etc.), and administration and governance (implementation of mechanisms for adherence to established regulatory frameworks, practice enhancements, policy recommendations, technical and assessment studies, etc.). The ultimate aim of urban planning is to make cities more sustainable and thus livable, safe, resilient, and attractive places. As an academic discipline, urban planning is concerned with strategic thinking, research and analysis, sustainable development, economic development, environmental planning, transportation planning, land-use planning, landscape architecture, civil engineering, policy recommendations, public administration, and urban design (e.g., Nigel 2007). Urban planning is closely related to the field of urban design and some urban planners indeed provide designs for neighborhoods, streets, buildings, parks, and other urban areas.

The research and practice in the field of smart sustainable cities tend to focus on the identification of the urban domains that are associated with sustainability dimensions (including transport, energy, environment, land use, mobility, traffic, healthcare, education, public safety, etc.)—on the basis of big data—for storage, processing, analysis, modeling, and simulation so to develop urban intelligence functions and simulation models for strategic decision-making and enhanced insights pertaining to urban planning processes (Bibri 2018). This also involves how those domains interrelate and can be coordinated and merged together for enhanced outcomes in terms of the contribution to the goals of sustainable development. The technical features of smart sustainable urban planning involve the application of ICT as a set of scientific and technical processes to land use, natural ecosystems, physical structures, spatial organizations, natural resources, infrastructure systems, socioeconomic networks, and citizens' services. Recent evidence (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri and Krogstie 2017b; Bibri 2018) lends itself to the argument that an amalgamation of these strands of urban planning with cutting-edge big data analytics as an advanced form of ICT can help create more sustainable and thus livable, safe, and attractive cities. In all, the data-driven approach to urban planning is of paramount importance to strategic sustainable urban development. Besides, the functioning, management, and organization of urban systems and related processes and activities in the field of sustainable urban planning require not only complex interdisciplinary knowledge of sustainability, but also sophisticated technologies and powerful data analytics capabilities.

Sustainable development goals and smart targets should be well understood with respect to their synergy and integration (see, e.g., Ahvenniemi et al. 2017; Angelidou et al. 2017; Batty et al. 2012; Bibri 2018; Bibri and Krogstie 2017b; Bifulco et al. 2016; Kramers et al. 2014) in the context of city planning, a valuable force for attaining a sort of integrated objectives in the realm of smart sustainable cities. As a management and government function, city planning involves formulating a detailed plan to achieve optimum balance of demands for growth with the available resources and the need to protect the environment, or to provide and maintain a livable and healthy human environment in conjunction with minimal demand on resources and minimal impacts on the environment—by integrating urban strategies with technological innovations as well as formulating and implementing policy regulations and institutional frameworks. In this respect, backcasting appears to be the most appropriate planning approach into smart sustainable city development due to the complexity of the problem at hand and the fact that different directions of development can be allowed given the wide scope and long time horizon considered.

Smart sustainable urban planning uses ICT and other means to guide and direct the use and development of land, resources, and infrastructures, the protection of the environment, and the distribution of ecosystem and human services—in ways that strategically assess and continuously improve the contribution of the city to the environmental, economic, and social goals of sustainable development. Thus, it involves a set of approaches into practically applying and effectively merging sustainability knowledge and eco-technology to the planning and development of existing and new cities. This entails working strategically toward maximizing the efficiency of energy and material resources, creating zero-waste systems, supporting renewable energy production and consumption, promoting carbon neutrality and reducing pollution, decreasing transport needs and encouraging walking and cycling, providing efficient and sustainable transport, preserving ecosystems, emphasizing design scalability and spatial proximity, and promoting livability and sustainable community (Bibri 2018). ICT is of fundamental importance to attaining such goals due to its constitutive nature and transformational effects.

What is known about the relationship between urban planning interventions, sustainability, and ICT objectives is a subject of philosophical debate. This means that realizing smart sustainable cities requires making countless and integrated decisions about urban form, urban design, sustainable technologies, and governance. Regardless, this endeavor should consist in adopting a holistic approach to decision-making, a pathway that can best be pursued by employing advanced technological systems and analytical methods, thereby the need for big data technologies and related data-driven decision-making with respect to urban policy design and analysis. As noted by Angelidou et al. (2017), the incorporation of the systematic use of big data in the policy development and monitoring process is a key success factor toward better policy design and implementation, with significant positive impacts on contemporary cities on multiple levels. To put it differently, new sources of urban data coordinated with urban practice and policy can be applied on the basis of the fundamental principles of data science and analytical engineering to devise powerful solutions to urban sustainability problems. Big data analytics for decision-making (basing the decisions on the analysis of big data) can be of wide use in different areas of urban planning. Indeed, big data uses are associated with optimization, control, automation, management, evaluation, recommendation, and improvement in relation to urban operational functioning, development, and governance in the context of sustainability (see Chap. 7 for further details). This should constitute an integral part of the detailed plan to be formulated based on backcasting for smart sustainable city development, where consideration is typically given to a wide array of sustainability issues, such as air pollution, traffic congestion, land use, energy consumption, legislation and regulation, and social policy. Smart sustainable urban planning is gaining special importance in, and its prominence is increasing throughout, the twenty-first century, as contemporary cities are increasingly facing enormous challenges pertaining to urbanization and sustainability. As a process, it identifies the goals of sustainable development to be achieved; formulates strategies to achieve them; arranges the means and procedures required; and implements, monitors, directs, assesses, and enhances all steps in their proper sequence. This is at the core of the backcasting approach to strategic planning for the development of smart sustainable cities of the future.

11.2.2 Strategic Smart Sustainable Urban Development

Sustainable urban development is an approach to achieve urban sustainability. There are several approaches to sustainable urban development, one of which is the strategic one which is guided by a shared understanding of sustainability principles that embody the end goal for achieving urban sustainability. The four sustainability principles are considered as basic principles for socio-ecological sustainability as developed through scientific consensus (e.g., Holmberg and Robèrt 2000). In the sustainable society, according to Holmberg and Robèrt (2000), nature is not subject to systematically increasing…

1. …concentrations of substances extracted from the Earth’s crust,
2. …concentrations of substances produced by society,
3. …degradation by physical means, and in that society…
4. people are not subject to conditions that systematically undermine their ability to meet their needs.

The purpose of articulating sustainability with scientific rigor is to make it more intelligible, more useful, and clearer for measuring, analyzing, and managing human activities within society. From an environmental perspective, for example, to be strategic in moving toward urban sustainability requires a clear understanding of sustainability principles concerned with environmental issues, which are employed to set the minimum requirements of an environmentally sustainable city. Sustainability principles define an end goal for urban sustainability to plan strategically and holistically to attain socio-ecological sustainability in the city. Strategic sustainable urban development is a planned development that addresses environmental, social, and economic issues in a rigorous, meaningful, and scientific way to achieve a sustainable city. This can occur through tackling the root causes that are resulting in the current systematic decline in the potential of the city so to help develop upstream and well-informed solutions needed to sustain the functioning of urban systems. Strategic sustainable urban development entails a backcasting from basic sustainability principles, whereby a desirable sustainable future is set as the reference point for devising and implementing strategic actions to attain that specified future, the actions needed to achieve the long-term goals of urban sustainability and all of the other critical elements developed during the backcasting exercise. This is necessary to act proactively as well as to think strategically, on a larger scale, and of future generations. Strategic sustainable urban development can be viewed as an alternative way of thinking to solve the escalating environmental problems and socioeconomic issues, thereby mitigating the negative impacts of the current path of city development. As such, it seeks to guide planners, organizations, governments, and institutions to agree upon concrete ways to take action together to implement sustainable urban development on a global scale.

The concept of sustainable development has been applied to urban planning since the early 1990s (e.g., Wheeler and Beatley 2010). The strategic process of sustainable urban development as a desired trajectory seeks to create healthy, livable, and prosperous human environments with minimal demand on resources (energy, material, etc.) and minimal impact on the environment (toxic waste, air and water pollution, hazardous chemicals, etc.). Richardson (1989, p. 14) defines sustainable urban development as “a process of change in the built environment which foster economic development while conserving resources and promoting the health of the individual, the community, and the ecosystem.” In a nutshell, sustainable urban development is characterized as achieving a balance between the development of and equity in the urban areas and the protection of the urban environment. However, conflicts among the goals of sustainable urban development to achieve the long-term goals of urban sustainability are challenging to deal with and daunting to overcome. This has indeed been, and continues to be, one of the toughest challenges facing urban planners and scholars as to planning in the realm of sustainable cities. Despite sustainable urban development seeking to provide an enticing, holistic approach into evading the conflicts among its goals, these conflicts “cannot be shaken off so easily”, as they “go to the historic core of planning and are a leitmotif in the contemporary battles in our cities”, rather than being “merely conceptual, among the abstract notions of ecological, economic, and political logic”

(Campbell 1996, p. 296). Even though these goals coexist uneasily in contemporary cities, sustainable urban development as a long-range objective for achieving the aim of urban sustainability is worthy for urban planners, as they need a strategic process to achieve the status of sustainable cities, to increase the contribution of smart cities to sustainability, and to spur the development of smart sustainable cites. As expressed by Campbell (1996, p. 9), planners will in the upcoming years "confront deep–seated conflicts among economic, social, and environmental interests that cannot be wished away through admittedly appealing images of a community in harmony with nature. Nevertheless, one can diffuse the conflict, and find ways to avert its more destructive fall–out." To put it differently, sustainable urban development advocates can—and ought to—seek ways to make the most of all three value sets at once. This is in contrast to keeping on playing them off against one another. With that in mind, the synergistic and substantive effects of sustainable development on forms of urban management, planning, and development require cooperative effort, collaborative work, and concerted action from diverse urban stakeholders in order to take a holistic view of the complex challenges and pressing issues facing contemporary cities.

In the context of this chapter, the smart dimension of sustainable urban development is also on focus. In this regard, the strategic process of smart sustainable urban development denotes a process of change in the built environment driven by ICT and other technological innovations that seek to promote sustainable built form, environmental integration, economic regeneration, and social equity as a set of interrelated goals. In other words, to foster economic development while conserving resources and promoting the health of the ecosystem and its users requires innovative solutions and sophisticated approaches resulting from unlocking the untapped potential and transformational effects of ICT in terms of its disruptive and synergetic power given its enabling, integrative, and constitutive nature. Such process ought to be based on amalgamating the research agenda of urban computing innovation and urban ICT development with the agenda of sustainable development and urban planning, thereby justifying ICT investment and its orientation by environmental concerns and socioeconomic needs within contemporary human settlements. This endeavor should in turn be supported by pertinent institutional structures and practices and policy frameworks and measures.

11.3 Futures Studies: Dimensions, Objectives, Types, and Approaches

Since the dawn of civilization, people have tried to develop methods for predicting the future. But in recent years, scientists, sociologists, researchers, and others futurists within different disciplines have developed qualitative and quantitative methods for rationally predicting the future. Rationality in this context of use signifies a recognition or awareness that many different futures are possible and that the future is far from being determined or known with absolute certainty. This is typically contingent upon the kinds of the decisions people make and action they take in the present. This chapter is concerned with a backcasting approach to futures studies on smart sustainable city development, and such studies do not pretend to be able to predict the future, although assessing the probabilities of alternative futures in this regard constitutes a key aspect of the approach to studying (smart sustainable cities of) the future. Futures studies are intended to assist decision-making under uncertainty which is to be defined as indeterminacy, rather than to predict the future (Dreborg 1996). The backcasting approach in this context is primarily designed to help people better understand future possibilities of models of smart sustainable urban form in order to make better decisions today. Indeed, the core purpose of futures studies is to get a better understanding of future opportunities as alternatives with their differences and feasibilities. These can be employed by the aligned stakeholders in a given endeavor to challenge present systems or to influence the future inspire it, or adapt to the most likely one. Creating a choice of futures by outlining alternatives usually forms the basis for planning. In light of this, futures studies help people to examine and clarify their normative scenarios of the future, to transform their visions, and then to develop action plans on the basis of a wide range of techniques. In the context of smart sustainable city development, they are basically used to provide an analytical framework for policy decisions in the identification of opportunities for integrating the novel applications of advanced ICT with the design concepts and planning principles of sustainable urban forms, and in assessing alternative actions of high strategic potential under different conditions. The role of futures studies has become of central importance for policymaking process in the context of urban sustainability. Such process is characterized by increasing complexity at the macro-level as well as by decreasing the extent of conditionality at the micro-level due to the mounting autonomy of individual actors (Miola 2008). This implies that social institutions are less powerful in affecting major changes through straightforward policy responses (Ling 2002).

Long lasting and substantive transformations, including sustainability transitions, can only come about through the accumulation of several integrated smaller scale actions associated with strategically successful initiatives and programs. They also operate at the interface of policy domains. Methods for futures studies can help to highlight such initiatives and programs and to identify such interface. In the context of city development, they can be used to illustrate what might happen to cities in order to allow them to adapt to perceived future trends. Researchers, scientists, and sociologists and other futurists employ methods for futures studies as an attempt to manage uncertainty rather than reduce it. As such, these methods aid in dealing with this uncertainty by clarifying what the most desirable possibilities are what can be known, what is already known, as well as how today's decisions and actions may play out in each of a variety of plausible futures. The effectiveness of futures studies lies in defining a broader conceptual framework for discussing the future as well as for contributing to policy formulation, transition governance, and the emergence of new possibilities. The kind of decision-making such studies seek to assist under uncertainty pertains especially to long-term decisions. In the context of smart sustainable cities, decisions are to be made in ways that reduce uncertainty about what may happen in the future in terms of urban development or analyze the effects of today's decisions taken in line with the vision of sustainability as enabled by advanced ICT in the future.

Futurists often divide the purpose of futures studies as assessing the probable, imagining the possible, and deciding on the preferable. As pointed out by Banister and Stead (2004). futures studies can be classified based on the three modes of thinking about the future:

- Possible futures (what might happen?). Scenario studies as descriptions of possible future states and their developments are included in this category (Borjeson et al. 2006).
- Probable futures (what is most likely to happen?). This category includes forecasting studies, which are characterized by a predictive nature and mainly focused on historical data and trend analysis.
- Preferable futures (what we would prefer to happen?). This category is of relevance to futures studies dealing with urban sustainability, as it involves studies focusing on normative or desirable futures, such as backcasting and normative forecasting.

Several authors have elaborated on futures studies in relation to sustainability. Dreborg (1996) identifies four different types of futures studies in connection with sustainability, namely:

- Directional studies which investigate different economics and other measures in the short term that will probably work in the right direction toward sustainability.
- Short-term studies which take immediate official goals as a starting point or a small step toward sustainability, and attempt to find means of achieving them.
- Forecasting studies which usually apply to a long-term perspective, but restricted presumptions of the possibilities of major change make this approach fail to reach sustainability.
- Alternative solutions and visions where the development of future (normative) scenarios as desirable futures allows them to be explored by using backcasting where the results describe a desirable future with criteria for sustainability providing the systemic framework for change.

There is no consensus on a single classification of futures studies or a guide for the application of the most suitable approaches to futures studies. Most methods for futures studies focus on one or two of these goals: assessing the probable, imagining the possible, and deciding on the preferable (e.g., Miola 2008). Futures studies on smart sustainable city development are concerned with deciding on the preferable in terms of how to prefer the development of such city to play out. In this regard, visioning techniques may provide information about the preferable as a result of visioning: the action of developing a preferred plan, goal, or vision for the future. They can also tell us about the possible as a result of brainstorming over a range of alternatives if we happen to focus on both the preferable and possible as goals. Further, beyond any kind of classification and focus, the researcher's worldview and aim are the most important criteria that determine how a futures study can be developed. Researchers will almost always need different methods to carry out their futures studies.

Being the most suitable methodological framework or planning approach to be pursued in futures studies dealing with urban sustainability, the backcasting approach is prescriptive (normative) by focusing on what smart sustainable cities of the future should be. Generally, prescriptive methods for futures studies try to aid people in clarifying their values and preferences so they can develop visions of desirable futures. Indeed, backcasting allows researchers to understand what they would prefer the future to be and then take the appropriate (or necessary) steps to create that preferred future. Methods for futures studies are also descriptive (extrapolative) in the sense of describing what the future will be or could be in an objective way. While many futurists strive for objectivity, most methods for futures studies as part of qualitative inquiry rely on subjective human judgment. Nevertheless, various tools have been developed and applied to mitigate such judgment through encouraging collective judgment, generating ideas to produce different judgments, and identifying discrepancies between competing views on the future, as well as substantiating consistencies and inconsistencies among and within such views.

There might be as many approaches to futures studies as futurists, since futurists develop different ways to look ahead or envision the future. But some consensus in this regard is evolving. According to Chatterjee and Gordon (2006), futures studies can be categorized on the basis of the context that is being studied in terms of simplicity and complexity. Specifically, if the context is predictable and largely controllable then a planning approach such as forecasting may be appropriate, and if it is unpredictable and uncertain an alternative approach such as scenario planning is more suitable (Chatterjee and Gordon 2006). Another consensual perspective among futurists is the need to employ multiple approaches to address most futures problems. In this chapter, the intent is to devise or craft a backcasting as a planning method for smart sustainable city development, complemented by insights drawn from trend analysis and scenario planning. There is an argument that supports the idea of developing future research programs that integrate various approaches to futures studies to gain much greater insight than relying on a single approach. There are a number of different approaches to strategy and future analysis that investigate what will, could, or should happen in the future that are in their application not mutually exclusive. The following approaches to futures studies are preferably to be combined in futures studies. The backcasting approach, which is the focus of this chapter, is addressed separately in more details in the next section.

11.3.1 Cyclical Pattern Analysis

This futures study method is closely related to trend analysis. Many environmental, economic, and social phenomena seem to operate in cycles. It uses cyclic or recurring patterns in the form of waves, bursts, epochs, and episodes to anticipating future developments in various domains, such as city development, environmental change, public policy, and economic/financial system. Futurists concerned with cyclical pattern analysis have explored different kinds of cycles, including societal cycles (e.g., a pattern of long waves characterized by recession, depression, recovery, and prosperity), historical cycles, ecosystem cycles, environmental cycles, generational cycles, product life cycles, and business cycles.

11.3.2 Trend Analysis

A trend denotes a pattern of change over time in some phenomena of importance and relevance to the observer. As a common futures study method, trend analysis involves the use of a variety of techniques based on historical data. Quantitative trend analyses are often applied to areas involving solid and large historical data. The mechanical methods such as time series, trend extrapolations, forecasts, cycle analyses, and long waves analyses that are used to analyze historical sequence data are based on complex statistical analyses or mathematical structures (e.g., Chatterjee and Gordon 2006). The main strength of mechanical projection is the objectivity of this process (Banister and Stead 2004). This implies the possibility of testing the accurate application of the method and of evaluating statistically its validity in an applied setting (Miola 2008). The key issue with quantitative trend analyses is the propensity to accept their results as a kind of truth about the future rather than simply a starting point for discussion (Banister and Stead 2004). Such analyses remain most suitable for projecting forward in a stable or nonlinear system.

Also, trend analysis involves the use of a variety of techniques based on several processes. One of which is identifying a shift in the world around us, that is, spotting an emerging trend (e.g., ubiquitous and sentient cities within technologically advanced nations, Ambient Intelligence in the European society, and big data analytics in the economic sector). In this context, one needs to do some analysis to understand the nature of the trend and its potential implications. One could first look at historical data to identify some patterns, and then might extrapolate the trend into the future to predict that such cities would spread more in the years ahead due to their, for example, social benefits. Indeed, trend analysis requires more than a simple extrapolation of the trend into the future, namely probing what is causing the trend, whether those causes continue undoubtedly and indefinitely in that direction, if there are some limitations to the trend, what other external forces may affect the trend, and whether the trend is part of rather a larger societal shift with far-reaching and long-term implications (e.g., sustainability, urbanization, and ubiquitous computing).

Like most methods for futures studies, trend analysis relies more on subjective judgment rather than objective extrapolation of historical data. As an objective component of trend analysis, extrapolation is straightforward and essentially consists of taking historical data, fitting a curve or a range of values to the data, and extending these into the future by inferring unknown attributes from trends within the known data. In general terms, extrapolation is the process of estimating some kind of phenomenon by assuming that existing trends will continue or a current method will remain applicable. At this point, the assumption underlying trend extrapolation is that things will follow the same shifting pattern in the future as in the past. One simply extends the curve forward to estimate how things will evolve up to, or where they will be at, a certain future time. A good example of trend analysis is the phenomenon of urbanization. If the world's population living in cities is known to represent more than half by 2007, by 2050 it will be more than two-thirds (United Nations 2015d). That is to say, if the global urban population is known to be increasing at the rate of 2 people every second, we assume that it will continue to do so in the future, and we can use simple arithmetic to calculate what the population will be in 10, 20, or 30 years. To put it differently, a forecast can be generated by observing a (longer term) global shift through time in the character and pace of urbanization and projecting (extrapolating) that shift into the future, while disregarding short-term fluctuations. In fact, trend analysis is often criticized for its lack of creativity and consideration of potential changes; there is a tendency to overlook less predictable possibilities and solely to project from the past to the future in a straight line (Miola 2008).

Trend extrapolation is a commonly used method for generating a forecast by many urban planners who constantly extrapolate trends, whether consciously or unconsciously, when looking ahead or thinking about the future. One of the most sensible ways to attempt to understand the future as to how cities will evolve is assuming that the future will mirror the past or that the past will exhibit shifting patterns in the same direction, rate, or pace toward the future.

11.3.3 Technological Forecasting

Forecasting is used to predict the most likely future, projected forward over a specific time horizon (e.g., coming weeks, months, or years) based on the previous or current trends. With the focus of technological forecasting being on the subject area of the forecasts rather than the approach employed, it could theoretically use almost any of the existing approaches to futures studies. This feature differentiates technological forecasting from the other existing methods, which makes it a sort of an independent method. As such, technological forecasting has its own concepts, techniques, and practitioners, representing a distinct endeavor within futures studies. One of the subject areas where forecasting is mostly applied is ICT development. Within the framework of technological development, forecasting concerns "the extrapolation of developments toward the future and the exploration of achievements that can be realized through technology in the long term" (Jansen 1994, p. 503). Accordingly, forecasts can be made on how soon some disruptive technologies or computing paradigms (e.g., Ambient Intelligence, the IoT, and Big Data) will be achievable and deployable and what characteristic features they may possess depending on economic, social, political, and environmental considerations. These are considered as external (non-technological) factors that are normally beyond the ambit of technology forecaster. A key concept adopted in technological forecasting is what is labeled "stages of innovation." According to Martino (2003), these stages, which every technological advance goes through and represent a greater degree of use, include:

Scientific findings, when some basic scientific understanding has been developed.
Laboratory feasibility, when a specific solution to a specific problem has been identified and a laboratory model has been created.
Operating prototype, when a device intended for a particular operational environment has been built.
Commercial introduction or operational use, at which point the innovation is technologically successful but also economically feasible.
Widespread adoption, at which point the innovation has shown itself to be in some way superior to whatever method was used previously to perform its function and the innovation replaces some portion of those previous methods.
Diffusion to other areas, at which point the innovation becomes adopted for purposes other than those originally intended.
Social and economic impact, at which point the innovation has changed the behavior of society or has somehow involved a substantial portion of the economy.
For a review of selected recent advances in technological forecasting, the interested reader can be directed to Martino (2003). In this work, the author describes developments in environmental scanning, models, scenarios, extrapolation, Delphi, technology measurement, probabilistic forecasts, and some chaos-like behavior in technological data.

Foresight is one of the most commonly used techniques in technological forecasting. It is typically concerned with a time frame ranging from 5 to 30 years as a long-term look into the future. As a process, it involves the interaction between many societal stakeholders, including academia, the scientific community, policymakers, government, industry, and other economic sectors. Foresight can be defined as a "systematic, participatory, future-intelligence-gathering, and medium to long-term vision building process" (FOREN 2001). Central to foresight exercises are expert consultations, which, in turn, can use such techniques as Delphi method, brainstorming, and scenario-writing analysis to design roadmaps of future technological developments (Miola 2008). Delphi method aims at facilitating an expert discussion and enables anonymity of the participants. It involves surveying experts' opinion consecutively over a period of time to identify trends and changes and to gradually achieve a convergence of opinion (e.g., Martino 2003). Foresight exercises have been employed for several purposes (Miola 2008):

To forecast developments and changes in the areas of technology, environment, economy, science, and society, and hence to create policy strategies to meet challenges.
To define key areas of science and technology that are vital for economic development and hence that should be prioritized for funding.

To elaborate pathways of technology application, to create wealth, and to improve the quality of life whilst respecting environmental concerns.

Foresight attempts to prepare for and assess future challenges and changes involved in the long-term future, and the related strategies should focus on addressing these challenges and influence the changing process. In all, foresight is used as a means to anticipate not only technological changes but also environmental, social, economic, political, and institutional changes, and thus to formulate policy strategies accordingly.

11.3.4 Visioning

Visioning is the action of developing, or the process of intensely making images of, the desired future (plans, goals, objectives, outcomes) sufficiently real and compelling to act as a stimulus or spur to the present action. It also refers to the fact of seeing visions. As such, it can be carried out by an individual or a group of people. A wide array of techniques have been developed by different futurists for aiding people in developing their vision of desirable futures pertaining to organizations, communities, cities, and societies. The importance of seeing visions of the future, which usually materialize subsequent to new scientific discovery and its technological applications, lies in that these visions "have the power not only to catch peoples" minds and imaginations, but also to inspire them into a quest for new possibilities and untapped opportunities and to challenge them to think outside common mindsets' (Bibri 2015b, p. 3). The techno-urban vision of smart sustainable cities, which is constructed in the light of new conceptions about the scientific, technological, environmental, economic, institutional, social, and cultural changes over the past few years—contains an all-embracing understanding of the problems cities are facing and is also the defining context for suggested ICT solutions as future possibilities for the challenge of urban sustainability and urbanization (Bibri and Krogstie 2016). The ICT of computing orientation of the development of sustainable city has gained dominance in ecologically and technologically advanced societies under the vision of smart sustainable cities. This implies that this vision has gained legitimacy as an academic discourse and thus urban planning practice—i.e., pursued through diverse urban development strategies and projects and supported by research and innovation endeavors and policy measures. In particular, the growing academic interest in smart sustainable cities is such that it has become part of mainstream debate in sustainable urban planning and city-related disciplines. This is because of the (perceived) potential of innovative ICT to catalyze and boost sustainable urban development processes and thus to advance urban sustainability. In addition, the vision of smart sustainable cities and its translation into hegemonic techno-urban strategies and projects and their ongoing institutionalization in urban planning and development structures and practices postulate that future visions of noteworthy advances in science and technology (computing and ICT) bring with them wide-ranging visions of the future on how cities will evolve and the opportunities such future will bring with regard to, for example, sustainability, efficiency, and the quality of life.

In all, a visioning process will challenge people's current assumptions, identify sources of pleasure and dismay in the past and present, and induce people to understand and embrace current drivers of change so they can imagine a range of alternative futures. This is crucial to facilitating the generation of some consensus of a desirable future or preferred vision for the future. More importantly, a vision is a compelling, inspiring statement of the preferred future that those who subscribe to it want to create and make real. However, from a research perspective, there are important risks in such a focus on an inspiring, compelling technological vision of the future, including neglecting the challenges of the present, the techno-utopian discourse, and the exclusion of alternative visions due to too much convergence on a single vision of the future. For a detailed account of these risks in relation to Ambient Intelligence as an inspiring, compelling vision of the future, the reader can be directed to Bibri (2015b). Another common risk is that scenarios as a representation of visions of the future may turn out to be wrong. Nonetheless, they do serve to promote debate, foster understanding, create fertile insights, and provoke thought. In relation to the vision of Ambient Intelligence, José et al. (2010, p. 1482) state, "after almost 10 years of considerable research effort, it is now possible and timely to look back at the visionary scenarios, the research results, and reflect on the overall accomplishments of this area. Overall, we should recognize that we now have a much more thorough understanding of the problem domain and also appropriate solutions to some of the specific issues involved. However, we must also acknowledge the existence of a persistent gap between the promises of the area and its real achievements. In particular, some of the central features of AmI, such as its anticipatory nature or strong personalization, are not only far from being achieved, are also being increasingly questioned."

Bezold (2000) identifies five stages in building a vision:

Identification of problems
Identification of past successes
Identification of future desires
Identification of measurable goals
Identification of resources to achieve those goals.

The ability of inventing and creating the preferred future is conditioned by the extent to which we can clearly articulate what we want. A preferred future involves our ideals as depicted in a vision statement as well as our sense of the best outcome that might be achievable (Bezold 2000). Dator (2004), a known expert of the visioning method, emphasizes the role of the futurist in helping people think more broadly about alternative futures. He argues that people engaging in any kind of preferred future envisioning exercise must first be challenged to examine their own ideas about the future, and their role is to present, in a dramatic, engaging way, some of the components or forces of the past and present that might have significant impacts on the future.

11.3.5 Scenario Planning

Scenarios are about making stories about the future, and usually have more specific detail than backcasting. They represent a series of events that we envision or imagine happening in the future. Visionary scenarios are part of everyday thinking in that it is filled with some ventures into the unknown or mysterious world of the future, tomorrow, next week, next year, or next decade. The more elaborate scenarios (e.g., a generation of simulation games for policymakers combining known facts about the future with key driving forces identified by considering environmental, economic, social, political, and technological trends) are usually developed by professional researchers (or groups of analysts) working for government agencies in relation to different domains, or for organizations and institutions. These often use scenario thinking/analysis as a practical method of planning for the future, despite the speculative nature of futurist scenarios and their overlap with science fiction. Scenario planning is an approach to strategic planning that some government agencies, organizations, and institutions use to make flexible long-term plans or to explore alternative futures. They can characterize multiple scenarios, then explore their implications for different purposes.

A scenario involves the question of what would happen if something occurred. For example, a scenario planning trigger question could be "What would happen if humans were 'surrounded and accompanied by advanced sensing and computing devices, multimodal user interfaces, intelligent software agents, and wireless networking technology, which are everywhere, invisibly woven into the fabric of space, in virtually all kinds of everyday objects in the form of tiny microelectronic processors and networks of miniature sensors and actuators'" (Bibri 2015a). Once this question is posed, we can begin to imagine the various consequences of the event. First, certain preparations would be necessary for this event to occur. The following are two examples of scenarios as envisioned in Ambient Intelligence:

One scenario is where AmI is used to optimize traffic and goods delivery by creating smart traffic and smart delivery in order to minimize ecological impact and maximize urban efficiency. Carmen is further out on the time horizon because it implies major infrastructure developments. It also makes significant assumptions about changes in public behavior such as accepting ride shares and traffic management systems (ISTAG 2001, p. 13).

Another scenario is where AmI is used to enhance the learning experience on a spontaneous basis and to establish a "collective learning memory". This scenario is probably the furthest out in terms of time because it implies significant technical developments such as high "emotional bandwidth" for shared presence and visualization technologies, or breakthroughs in computer-supported pedagogic techniques.

In addition, the scenario presents a challenging social vision of AmI in the service of fostering community life through shared interests (ISTAG 2001, p. 14).

We may develop a large number of scenarios in an effort to decide whether or not to deploy Ambient Intelligence technologies. Scenario planning is one of the most commonly used methods in technology foresight (see ISTAG (2001) for a set of visionary scenarios related to the vision of Ambient Intelligence). Here internally consistent narrative descriptions of development in the future are used in the process of scenario planning. Such descriptions also involve possible states of affairs. Scenario planning requires a serious effort to make the scenarios as realistic as possible. To put it differently, scenarios can be described as a representation of visions of the future and courses of development organized in a consistent and systematic way. In the context of smart sustainable cities, a scenario is a narrative description of a smart and sustainable city's current situation of possible and desirable future urban situations and a series of events that can occur between current and future situations (see Becker et al. 1982). As an approach to futures studies, scenarios are the most frequently used method. A scenario is described by Rotmans and van Asselt (1998) as archetypal images or visions of the future, created by mental models that reflect different perspectives on past, present, and future developments. Emphasizing the distinction between scenarios and visions of the future, Banister (2004) notes that the former is dynamic, logical sequences of events, whereas the latter is often static "snapshots" in time.

There are different types of scenarios depending on the perspectives and objectives of the scenario setters and their use. Ling (2002) draws a useful distinction between the "visionary model", the "precautionary model", and the "learning model" of scenario writing. The Ph.D. study is concerned with the visionary model. Under it, a preferred future is designed and then strategies for reaching this future are outlined using the so-called backcasting approach (Banister and Stead 2004). The aim of the precautionary model approach is to envisage a negative future state resulting from a series or a certain course of events as a way to make explicit the negative consequences of present actions and to devise some elaborate ways to counteract such consequences (Miola 2008). In addition, following Rotmans's taxonomy (2000a, b), scenarios can be classified into different categories, including:

Projective and prospective scenarios: A starting point of projective scenario (forecasting) is the current situation and the extrapolation of current trends into likely future images. A prospective scenario (backcasting) departs from a desirable future situation, depicted as a set of goals or targets established by the assumed events between the current and future situations.

Qualitative and quantitative scenarios: As a form of narrative used in cases where data are missing or weak, a qualitative scenario describes the future in the form of words or visual symbols. A quantitative scenario provides numerical information and is based on models containing many implicit assumptions about the future.

Descriptive and normative scenarios: A descriptive scenario lists a set of possible events without taking into account their desirability, whereas a normative scenario takes values and interests into account and entails reasoning from specific targets which have to be achieved.

Participatory and expert scenarios: A participatory scenario involves various stakeholders to co-design scenarios with experts, whereas an expert scenario involves a small group of experts who are responsible for their design and development.

In relation to participatory scenarios, a principle upon which some consensus is evolving is that futures studies should be participatory: they should involve different stakeholders and decision-makers as well as experts in the process of creating scenarios. This is predicated on the assumption that a wide participation allows people to fully see and appreciate the range of possible futures. Especially, as the emphasis has shifted from energy to sustainability since the early 1990s, a development toward participatory backcasting has taken place utilizing inputs from a broad range of stakeholders.

Furthermore, scenario can be categorized taking into account their geographical scales (i.e., global, international, national, and subnational regions), the level of integration (i.e., vertical integration in terms of cause and effect chains within one issue and horizontal integration between different domains), and varied time horizons (i.e., less than 10 years, less than 20 years, one generation, two generations, and beyond) (Miola 2008).

Usually, the objective of developing scenarios is to allow people to conceptualize alternative futures and to shed light on the potential effects of present developments and related decisions and actions. As hypothetical sequences of events constructed with the objective to focus attention on causal process and decisions points, scenarios serve as tools for ordering our perceptions about alternative futures in which today's decisions may develop in a particular way. First, they make us aware of potential problems that might occur if we were to take the proposed decision, e.g., the environmental risks of smart cities due to the adverse effects of ICT on resource depletion and energy consumption (see Bibri and Krogstie (2016, 2017b) for a discussion). The reasoning behind this is to rethink or abandon the proposed action and then prepare to take precautions that will mitigate the environmental risks that might result from a wide deployment of ICT across the city, including the current approach to ICT design and development.

Commonly, futures studies can be viewed as consisting of five stages:

The identification and monitoring of change
The critical analysis of change
The envisioning of alternatives
The envisioning of the preferred alternative
The planning and implementation of steps to achieve the preferred vision.

Depending on the nature of the futures study, many researchers or professionals will focus on their endeavors on two or three stages and leave the rest to other endeavors.

11.4 Backcasting Approach to Strategic Planning

11.4.1 Historical Origins and Characteristic Features

The term “backcasting” was coined by Robinson (1982) in the description of policy analysis approach. The backcasting approach was originally developed in the 1970s as an alternative to traditional energy forecasting and planning, and employed as a novel analytical tool for energy planning using normative scenarios. Backcasting studies concerned with energy dealt particularly with the so-called soft energy policy paths, characterized by the development of renewable energy technologies and a low-energy demand society (Quist and Vergragt 2006). At the time, such studies emerged as a response to regular energy forecasting, which was mainly based on trend extrapolation and projections of energy consumption, with a focus on large-scale fossil fuel and nuclear technologies. By developing an energy backcasting approach, the focus became analysis and deriving policy goals (Robinson 1982). Around the 1990s, a few years after the inception of sustainable development, the emphasis on backcasting shifted toward the identification and exploration of sustainability solutions in Sweden (Dreborg 1996), Canada (Robinson 2003), and the Netherlands (Weaver et al. 2000). Such solutions pertain to a wide range of topics, including transportation and mobility (Banister et al. 2000), sustainable technologies and sustainable system innovation (Weaver et al. 2000), sustainable household (Green and Vergragt 2002; Quist et al. 2001), transforming companies into sustainable ones (Holmberg 1998), sustainable urban design (Phdungsilp 2011), sustainable transportation systems (Akerman and Höjer 2006; Höjer 2000; Roth and Kaberger 2002), and sustainable city development (Carlsson–Kanyama et al. 2003). In light of these endeavors, it has been corroborated that the distinctive characteristics of backcasting as a planning approach make it specially appropriate for sustainability applications (e.g., Holmberg 1998; Holmberg and Robèrt 2000; Dreborg 1996). This has to do with the idea of taking a range of sustainable futures as a starting point for analyzing their feasibility and potential, as well as possible ways of attaining those futures (e.g., Quist et al. 2006). For a more detailed overview of past and present applications of backcasting, the interested reader can be directed to Quist and Vergragt (2006).

Backcasting is concerned with—how desirable futures can be created and attained—rather than what future states of affairs are likely to occur. In other words, backcasting is not concerned with predicting the future; rather, it is a strategic problem-solving framework, in the quest for the answer to how to reach specified outcomes in the future. This involves finding ways of linking goals that may lie more than a generation in the future to a set of steps performed now and designed to achieve that end. Therefore, backcasting is used in cases when it is desired to actively dictate a future outcome rather than merely predicting it. In backcasting, one envisions a desirable future endpoint, and then works backward to determine what programs would be required to attain that specified future, or to construct a plausible causal chain leading from here to there. In more detail, backcasting as closely related to scenario planning involves an imaginary scenario moving backward in time in as many different stages as are considered necessary as to connecting the future to the present to uncover the mechanism through which the present actions could lead to attaining that particular future scenario. Robinson (1990, p. 823) defines backcasting as a normative approach which works "backwards from a particular desired end point to the present in order to determine the feasibility of that future and what policy measures would be required to reach that point."

In general, the backcasting approach is applicable in futures studies dealing with the fundamental question of backcasting, which involves the kind of actions that must be taken to achieve a long-term goal. In a more specified way, as stated by Tinker (1996), "if we want to attain a certain goal, what actions must be taken to get there?" Here, backcasting means to look at the current situation from a future perspective. After envisioning a successful outcome in this future scenario, then comes the question of what can be done today to achieve that outcome. This enables us to ensure that strategies and actions are in the direction we want head. Accordingly, smart sustainable cities as future desired conditions are envisioned and appropriate actions and strategies are then defined to attain those conditions. Envisioning such cities has a normative side in terms of what future is desired, and backcasting the preferred vision of the future has an analytical side in terms of how this desirable future can be attained. In urban sustainability, planning is about figuring out the "next steps" which are quite literally the next concrete actions to undertake. Next steps are usually based on reacting to present circumstances, creativity, intuition, and common sense, but also (conceivably) are still aligned with the future vision and direction. A next step question of relevance to futures studies dealing with smart sustainable city development would be, for example, "To better monitor, understand, analyze, and plan sustainable urban forms to strategically assess, improve, and sustain their contribution to the goals of sustainable development, what is the very next thing we have to do?" Important to note, though, is that researchers in backcasting should not get obsessed with the next steps without considering how aligned they are with what they ultimately aim to achieve. Indeed, in the specific case of sustainability, it is as crucially important to undertake the first steps as to have lofty visions, thereby sustaining momentum by explicit, shared vision of success and being able to use that to guide the next steps.

Furthermore, since the notion of smart sustainable cities in this case is more a vision/image of the future than a reality, it is per definition normative, implying a certain desired view on the city within ecologically and technological advanced nations. By the same token, the backcasting approach is normative in the sense of establishing and deriving from an evaluative norm or a standard for making judgments about outcomes. Concerned with human societies, normativity is the phenomenon of designating some desirable or permissible actions. Many researchers tend to restrict the use of the term "normative" to the evaluative sense (Bicchieri 2005, 2017). In relation to backcasting, in consultation exercises as part of the normative-oriented visionary model of scenario writing, further insights can be gained by comparing different normative scenarios arrived at or generated by different stakeholders.

11.4.2 Backcasting Versus Forecasting

Backcasting stands out as an alternative to traditional forecasting (Robinson 1990). Backcasting approaches the challenge of discussing the future from the opposite direction of forecasting (Holmberg and Robèrt 2000). Forecasting is the process of predicting the future based on monitoring and analyzing current trend, that is, making statements about the future based on explicit or implicit assumptions drawn from the present situation in terms of observed trends. In other words, it starts the planning procedure from today's situation and projects today's trends and realistic solutions into the future (Dreborg 1996). This is commonly used in futures studies dealing with technological development and smart cities in the sense of defining steps that are merely a continuation of present developments extrapolated into the future (e.g., urban computing). As explained by Jansen (1994, p. 503), "Within the framework of technological development, 'forecasting' concerns the extrapolation of developments toward the future and the exploration of achievements that can be realized through technology in the long term. Conversely, the reasoning behind 'backcasting' is: on the basis of an interconnecting picture of demands technology must meet in the future—'sustainability criteria'—to direct and determine the process that technology development must take and possibly also the pace at which this development process must take effect. Backcasting [is] both an important aid in determining the direction technology development must take and in specifying the targets to be set for this purpose. As such, backcasting is an ideal search toward determining the nature and scope of the technological challenge posed by sustainable development, and it can thus serve to direct the search process toward new—sustainable—technology." This is of high relevance to smart sustainable cities with regard to interconnecting picture of demands such cities must meet in the future through integrating ICT and sustainability to direct and determine the process that urban development must take and also the pace at which such development must take effect. This perspective differs from what tends to be common in the framework of smart city development in terms of forecasting which concerns the extrapolation of ICT developments toward the future and the exploration of achievements enabled by innovative solutions that can be realized through ICT in the long term (e.g., big data analytics).

According to Dreborg (1996), backcasting is an approach to facilitating discovery, which is different from the more commonly applied forecasting approach. A significant difference between the two approaches is in the attitude taken toward uncertainty (Dreborg 1996). As further elucidated by Miola (2008, pp. 18–19), "in the forecasting approach the uncertainty is usually treated in terms of sensitivity of the model results to variations in external variables. The futures studies of forecasting have as idea to figure the future out what will really happen in order to permit society… to adapt to the more or less inevitable trends. In the forecasting approach it is impossible to predict our own future decisions to the extent that they are influenced by future knowledge. They often are total causal model. The backcasting approach takes into account the indeterminacy of the future and tries to define a broader conceptual framework for discussing the future; the study is less vulnerable to unforeseen change. This kind of studies may give an impulse for new knowledge."

Further, Dreborg (1996) distinguishes between backcasting studies and forecasting studies at different levels, as illustrated in Table 11.1. However, Höjer and Mattsson (2000) suggest that backcasting and forecasting are complementary.

In all, backcasting is a way of constructing a desirable future, whereas forecasting is a way of predicting a likely future state of affairs. Of importance to underscore in this regard is that in a backcasting process, a desirable future is the starting point when constructing the strategy, while in a forecasting process, the present trends and situations are key factors (Roth and Kaberger 2002). Figure 11.1

Table 11.1 Backcasting and forecasting five levels

	Backcasting	Forecasting
1. Philosophical view	Causality and teleology Partial indeterminacy Context of discovery	Causality Determinism Context of justification
2. Perspective	Societal problem in need of solution Desirable futures Scope of human choice Strategic decisions Retain freedom of action	Dominant trends Likely futures Possible marginal adjustments How to adopt trends
3. Approach	Define interesting futures Analyze consequences, and conditions for these futures to materialize	Extrapolate trends into the future Sensitivity analysis
4. Method	Partial and conditional extrapolations Highlighting interesting polarities and technological limits	Various econometric models
5. Techniques		Various mathematical algorithms

Source Dreborg (1996)

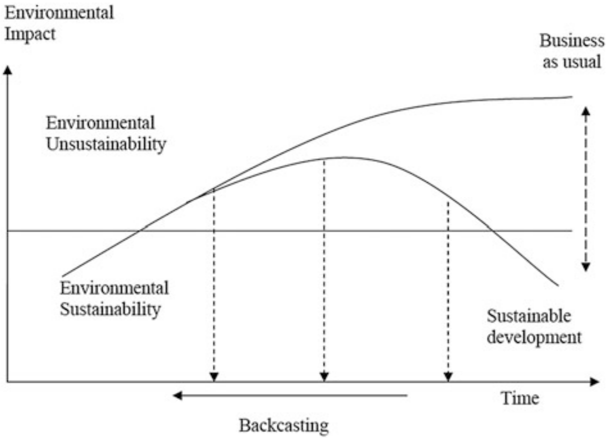

Fig. 11.1 Backcasting and forecasting approaches in a sustainability framework. *Source* Banister (2006)

summarizes the backcasting approach in comparison with the forecasting approach in a sustainability framework.

11.4.3 The Relevance and Purpose of Backcasting as a Scholarly Methodology for Strategic Smart Sustainable City Development

Qualitative research involves a range of approaches into data collection and analysis that researchers typically rely on to investigate a wide range of sustainability issues related to the physical, environmental, technological, economic, and social dimensions of the city, or a combination of these. The choice of any qualitative approach depends largely on what the researcher intends to investigate. In the context of futures studies dealing with strategic smart sustainable city development, backcasting as a problem-solving and planning approach is well suited to be adopted as a methodological framework for scholarly research—e.g., to investigate and analyze the development of a future model for smart sustainable city (e.g., Bibri 2018).

In terms of its practical applications, backcasting as a scholarly and planning approach is increasingly used in futures studies in fields related to urban sustainability (e.g., Miola 2008; Phdungsilp 2011) as an alternative to traditional planning approaches and a formal element of future strategic initiatives. This is of high relevance to smart sustainable city development as an area that involves both domains (Bibri 2018). The complexity of smart sustainable city planning, due to the current trends and actions being part of the problem, highlights the importance of applying the backcasting approach to have an informed vision of specific goals in order to strategically deal with potential trade-off among different decisions and actions. In this line of thinking, backcasting from system conditions of sustainability (or sustainability principles) is a key concept of the "Framework for Strategic Sustainable Development" pioneered by Karl-Henrik Robèrt, founder of The Natural Step, an international nonprofit organization dedicated to applied research for sustainability, in cooperation with a global academic Alliance for Strategic Sustainable Development which links universities which cooperate with industries and businesses. Backcasting from sustainability principles is the primary context in which The Natural Step Framework and Strategic Approach to Sustainable Development become so powerful.

In recent years, backcasting has become the most commonly applied approach to long-term futures studies on sustainable development, thereby their appropriateness for strategic smart sustainable city development. Researchers working within various urban domains as well as within the field of smart cities and sustainable cities have endeavored to understand and act in relation to sustainable development by describing visionary (normative) scenarios of a long-term future and justifying their potential realization on the basis of established theories and academic disciplines and discourses in conjunction with in-depth analyses of case studies (i.e., strategies, projects, programs, and successful practices) in a bid to stimulate an accelerated movement toward urban sustainability. This implies that a large body of research within the field of smart sustainable cities is being, and will be, founded on long-term futures studies of different sorts. One strand of such studies concerns itself with the way such cities amalgamate sustainable development goals and smart growth targets in an integrated approach due to the synergetic and disruptive effects of emerging and future ICT, particularly on urban operational functioning, management, and planning that are required for future forms of urban sustainability. The evolving body of futures studies in this direction constitutes a strategic resource for understanding the untapped potential of advanced ICT and its enabling, integrative, and constitutive nature for advancing urban sustainability. This involves the identification of the interconnections, relationships, and complexities associated with spatial and temporal scales in relation to urban analytics and planning using big data analytics for assessing, improving, and sustaining the contribution of smart sustainable cities to the goals of sustainable development.

The backcasting approach to strategic planning aids in determining the direction smart sustainable city development must take and in specifying the targets to be set for this purpose. As such, it represents a quest for identifying the nature and scope of the issues and challenges posed by the existing models of sustainable urban forms. And hence it serves to direct this quest toward—smart sustainable cities of the future. In other words, it sets the conditions for creative tension that motivates—the gap between the existing models of sustainable urban forms (the current reality) and smart sustainable cities (the future potential).

The analysis part will be done by studying cases using the backcasting approach such as sustainable city and smart city strategies, projects, and initiatives, with a particular focus on the design concepts and planning principles of sustainable urban forms and the novel applications of ICT of pervasive computing for sustainability (see Bibri 2018 for a detailed account). The development part will be done by combining results from the analysis with insights on how sustainability criteria can be formulated, especially in relation to the goals of sustainable development and what it means for a smart sustainable urban form as a process-oriented development approach to work with such criteria.

The purpose of backcasting studies in this regard is to create knowledge that can be used to guide complex urban transitions toward sustainability in an increasingly computerized and urbanized world. The end result thereof is alternative visions/images of the future, thoroughly analyzed as to their feasibility, potential, and consequences. In this respect, the process of backcasting involves establishing the description of a very definite and specific future situation in the form of principles and well-designed goals—i.e., how smart solutions for sustainability and sustainable urban forms' design concepts and planning principles can be integrated in the form of programs that must be supported by policy measures. A normative scenario can be defined and then a stepwise back move in time is done from that scenario to the present in order to determine the necessary decisions and actions pertaining to urban planning, urban technology, and urban policy that must be taken at critical points if that scenario is to be attained.

In this particular context, backcasting planning can be viewed as changing mindsets about the way sustainable urban forms can function and be understood, monitored, analyzed, planned, and developed, prior to formulating specific strategies. Backcasting is explicitly intended to suggest the implications of various desirable futures, chosen on the basis of criteria defined externally to the analysis (e.g., sustainability and ICT as of desirability) rather than on the basis of their likelihood (see Miola 2008). Additionally, Dreborg (1996) argues that backcasting is particularly useful when:

- The problem to be studied is complex and there is a need for major change;
- The dominant trends are part of the problem;
- The problem to a great extent is a matter of externalities; and
- The scope is wide enough and time horizon is long enough to leave considerable room for deliberate and different choices and directions of development.

The above is indeed of high relevance to the research problem of strategic smart sustainable city development. In complex systems like smart sustainable cities, and with complicated endeavors like sustainable development, backcasting is an effective approach to align various measures with each other, and thus to ensure that each activity is the logical platform for the next one, to draw on Robert (2000). In addition, backcasting is well suited for long-term problems and long-term sustainability solutions thanks to its normative and problem-solving character (Dreborg 1996). Furthermore, as pointed out by Robinson (1990), backcasting is not necessarily only about how desirable futures can be created and attained, but also about analyzing the extent to which undesirable futures can be responded to or avoided. Overall, backcasting studies must reflect solutions to a specified social problem in the broader sense (Dreborg 1996).

Projecting a transformative urban change that challenges existing assumptions for sustainable urban forms as a problem of significant complexity with a long enough time horizon to allow for making determined choices is the key role of backcasting in the futures studies dealing with smart sustainable city development. It is used to identify signals of sustainable urban change and also to determine short-term planning and policy goals that might facilitate long-term outcomes envisioned in future scenarios. In all, to backcast is mostly of pertinence when the future is uncertain and our actions are likely to influence, inspire, or create that future. To note, given that there is often greater uncertainty over what may happen in longer time frames, the future vision may usefully be described or defined using principles or well-designed goals rather than specifics.

11.4.4 *The Multiplicity and Adaptation of Methodological Frameworks for Backcasting*

In every situation, there is a way for many individuals, teams, and organizations to get clear on an agreed future vision of success to which all efforts can be directed and focused. The literature shows that there are a number of methodological frameworks applied in backcasting. The backcasting framework is adaptive in nature within its steps and thus guiding questions based on the specific context (academia, industry, government, etc.) under which it is applied, the stakeholders involved, and the complementary methods to be used (trend analysis, forecasting, scenario planning, visioning, etc.). The result is a process that can be considered more as a set of guiding principles and tools than as a strict adherence to the application of the approach as a process encompassing all the steps involved in a given backcasting methodology by soundly including the full set of guiding questions. Worth noting, the terms backcasting approach and backcasting methodology are differentiated in the literature. Quist (2007) clearly elaborates in his work that "backcasting approach" should be used to describe in general and more abstract terms, whereas "backcasting methodology" should be applied in such concrete cases. Regardless, there are several backcasting approaches or methodologies, and while these differ in their steps and thus guiding questions, they do converge on the essentials (as discussed below). Fundamentally, a backcasting study involves four steps (Höjer and Mattsson 2000), namely:

1. The setting of a few long-term targets
2. The evaluation of each target against the current situation, prevailing trends, and expected developments
3. The generation of images of the future that fulfill the targets
4. The analysis of images of the future in terms of feasibility, potential, and path toward images of the future (Akerman and Höjer 2006).

Robinson's (1990) backcasting approach uses such methods as social, economic, and environmental impact analysis; scenario construction methodologies; and system analysis and modeling The Natural Step (TNS) backcasting framework for sustainable development (Holmberg 1998; Robert et al. 2002) relies on such methods as creativity techniques, strategy development, employee involvement, and employee training. The Sustainable Technology Development (STD) backcasting approach (Weaver et al. 2000) employs such methods as stakeholder analysis, employee training, problem analysis, technology analysis, and construction of future visions.

The key assumptions of Robinson's backcasting approach include the following:

- Criteria for social and environmental desirability are set externally to the analysis;
- Goal-oriented;
- Policy-oriented;
- Design-oriented; and
- System-oriented.

The key assumptions of the TNS backcasting approach encompass the following:

- Decreasing resource usage;
- Decreasing emissions;
- Safeguarding biodiversity and ecosystem; and
- Efficient utilization of resources in line with the equity principle.

The key assumptions of the STD backcasting approach include the following:

- Sustainable future need fulfillment;
- Factor 20;
- Time horizon of 40–50 years;
- Coevolution of technology and society;
- Stakeholder participation; and
- Focus on realizing follow-up.

Backcasting can be described as an innovative participatory foresight approach to sustainability through construction of normative sustainable futures by a variety of stakeholders (Quist et al. 2006). The development toward participatory backcasting utilizing inputs from a broad range of stakeholders and discussions among them took place first in the early 1990s, a few years after the inception of sustainable development, and continued till today. During this period, backcasting has indeed been focused on the identification and exploration of sustainability solutions regarding a wide range of topics, and also shifted toward achieving implementation and follow-up. However, several questions have recently been raised concerning the adaptation of the complex transdisciplinary and participatory backcasting approach so that it can be suited to different projects or research endeavors. The factors triggering its adjustment accordingly involve the diversity in interests, mental frameworks, resources as well as the presence of dependencies between stakeholders and power issues among them in a regular backcasting project (Quist et al. 2006). As a scholarly methodology for strategic smart sustainable city development, the backcasting approach is not fully participatory, as it does not directly involve stakeholders from different societal groups. Nonetheless, it is informed by the knowledge of many experts, scholars, and scientists from relevant fields and professional domains, expressed in the literature (i.e., case studies, strategies, projects, and practices pertaining to smart sustainable city development). Backcasting projects with stakeholders in a real-life setting do involve stakeholders due to their position or influence in the field, their interests and stakes being at play, or their relevant knowledge about the problems and possible solutions; yet, they are not responsible for the application of the overall approach (or specific methods and tools) and its key feature of working from normative scenarios (desirable sustainable future visions) to activities and action agendas, so these are rather the responsibility of the facilitators (Quist et al. 2006). However, the fifth goal concerning stakeholder support, learning, and commitment for implementation (see Quist et al. 2006 for the full list of goals below) can still be realized in the context of smart sustainable city development given its benefits and underpinning foundations with regard to sustainability and ICT as influential theories and powerful large-scale societal discourses. But the backcasting exercise should be conducted by city governments or powerful urban actors as a group of societal stakeholders, rather than individual academic researchers or scholars. The goal pertains to making strategic action plans and considering the potential stakeholder support and commitment, ways to stimulate follow-up by stakeholders, and the instruments and measures that could support such activities (Quist et al. 2006).

As regards to the perspective on stakeholder involvement in futures studies where backcasting can be used as a scholarly methodology, the idea is to incorporate the views, assumptions, claims, and arguments (a set of reasons given in support of ideas, theories, and/or actions) of different experts, scholars, and scientists in the field of smart cities and sustainable cities in the analysis and development of future models for smart sustainable city. In addition to gathering data and facts, a range of stakeholder recommendations concerning such models and their feasibility and potential will be considered and included. Another emphasis of futures studies on smart sustainable city development is to provide suggestions for government, policymakers, and research bodies.

11.4.5 Methodological Frameworks for Backcasting—Participatory Backcasting

Several methodological frameworks for backcasting have been developed and applied in relation to sustainability. Phdungsilp (2011) compares three backcasting methodologies, namely Robinson's, TNS, and STD, as illustrated in Table 11.2.

As an explicitly normative and design-oriented, Robinson's approach aims to explore the implications of alternative development paths. However, it gives no standard recipe for generating scenarios, only some helpful guidelines and tools.

Table 11.2 Comparison of three backcasting methodologies

Robinson's methodology	TNS methodology	STD methodology
1. Determine objectives 2. Specify goals, constraints, and targets, and describe present system and specify exogenous variables 3. Describe present system and its material flows 4. Specify exogenous variables and inputs 5. Undertake scenario construction using the specified goals and constraints 6. Undertake scenario impact analysis	1. Define a framework and criteria for sustainability 2. Describe the current situation in relation to that framework 3. Envisage a future sustainable situation 4. Find strategies for sustainability	1. Strategic problem orientation 2. Develop sustainable future vision 3. Set out alternative solutions 4. Explore options and identify bottlenecks 5. Select among options and set up action plans 6. Set up cooperation agreements 7. Implement research agenda

Source Phdungsilp (2011)

The scenarios are evaluated in terms of socioeconomic, physical, and technological feasibility, and policy implications. Iteration of scenarios is usually required to resolve physical inconsistencies as well as to mitigate adverse economic, social, and environmental impacts that are revealed in the analysis. From a critical perspective, the approach puts a strong focus on technical analysis and policy recommendations, and neither specifies who is responsible for setting the criteria and future goals and how this will be done, nor includes stakeholder participation.

In Sweden, backcasting has been elaborated as a methodology for strategic planning toward sustainability, which has become known as the TNS Framework. Backcasting has been advocated and popularized by Karl–Henrik Robèrt, and thoroughly described by Holmberg (1998). Underlying the TNS approach is the way of thinking that the future itself cannot be predicted, but by viewing the physical principles of the ecosystem, a set of principles can be set to describe the future sustainable situation. This is based on four system conditions that should be simultaneously valid in a sustainable society (Robèrt 2000).

The STD approach relates to a Dutch government program, which focuses on achieving sustainable need fulfillment in the distant future. It involves a broad stakeholder participation, future visions, or normative scenarios, and the use of creativity to reach beyond existing mindsets and paradigms (Quist 2007). It has also been used for the integration of spatial functions.

There are some similarities and differences between the above three backcasting approaches. The overall approach provides a framework consisting of steps in which various types of methodologies can be applied. They all contain analytical methods and design methods. They moreover contain steps in which future visions or normative scenarios are constructed and the current situation is analyzed. Regarding the differences, the Robinson's approach and the TNS approach do not contain a separate backcasting step. They reserve the term backcasting for the overall approach. By contrast, the STD approach contains a separate backcasting step. Additionally, the TNS and the STD approaches contain steps dealing with operational aspects of implementation and follow-up, strategies, and agenda setting. Participatory methods are found in the TNS and STD approaches, but not in the case of Robinson's backcasting approach. In futures studies associated with strategic smart sustainable city development, the intent is to devise a generic methodological framework for backcasting planning by synthesizing Robinson's, the TNS, and STD and other approaches, which is the object of the next section. This scholarly methodology and planning approach could then be used to analyze and develop future models for smart sustainable city.

A methodological framework for backcasting can be synthesized based on different approaches (including Carlsson-Kanyamaa et al. 2003; Holmberg and Robèrt 2000; Quist 2009; Quist and Vergragt 2006), and encompasses five steps, namely:

1. Domain and demographics—Involves the clarification of the issues of the current state and the identification of the areas to be targeted and of all key and relevant stakeholders;

2. Future vision—Entails the definition and description of a desirable future or normative scenario in which the problems and issues identified have been solved by meeting the stated objectives;
3. Steps—Consists of developing possible steps (as well as addressing their feasibility) on how to reach the future vision from the present, addressing various dimensions (i.e., technological, social, cultural, political, institutional, and organizational) that require consideration;
4. Analysis—Involves assessing the developed future alternative, with the goal of creating an actionable plan while mitigating predicted threats and risks to successful implementation; and
5. Implementation—Is about establishing an action plan and putting it into motion while addressing the responsibilities of the key stakeholders concerned with the implementation of the results.

Quist and Vergragt (2006) and Quist (2002) distinguish several varieties of backcasting and put them into a methodological framework for participatory backcasting consisting of five steps, namely:

1. Strategic problem orientation;
2. Specification of external variables;
3. Construction of future visions or scenarios;
4. Backcasting: backward-looking analyses; and
5. Elaboration and defining follow-up and an action agenda.

In the first stage, normative assumptions are defined and goals are specified in relation to sustainability. The backcasting process starts off with defining the objectives with a description of the aim of the analysis in terms of its spatial, substantive, and temporal scope alongside the number and type of scenarios. The objectives are then translated into specific goals, constraints, and targets for scenario analysis and exogenous variables.

In the second stage, the exogenous variables are identified to describe the system not incorporated within the backcasting itself. The relevance of describing the broader context within which the analysis will take place lies in defining the different external elements that could act as direct inputs to the scenario analysis.

In the third stage, which is the core one of the backcasting process, the scenarios are constructed. This stage includes the development of future scenarios and the analysis of the future situation at the end and midpoints as well as the internal consistency of the scenario.

The fourth stage involves both design and analysis. It undertakes impact analysis by consolidating scenario results, which involves environmental, social, and economic effects and the consistency between the specified goals and scenario outcomes.

The fourth stage is usually linked to the policy process which constitutes part of the fifth stage. This aims at determining the political actions and institutional responses that are required for the implementation of the scenarios and the policy measures implied in those actions and responses.

Although this method is generally depicted stepwise and gives the impression that it is linear, it is definitely far from it. There is also a mutual influence between the different steps of the participatory backcasting approach following one another, and iteration cycles are likely to occur.

Of relevance to underscore is that Quist et al. (2006) remove the second step but add another one as a fifth step: Embedding of results and generating follow-up.

According to Quist and Vergragt (2006), four groups of tools and methods can be distinguished within the participatory backcasting approach, namely:

1. Participatory tools and methods which are useful for involving stakeholders and for generating and guiding interactivity among them;
2. Design tools and methods for constructing scenarios and for designing and elaborating stakeholder interaction processes;
3. Assessments of scenario and design such as environmental assessments and economic analysis, and also evaluation of social processes in the backcasting project and stakeholder analysis; and
4. Overall management, coordination, and communication tools and methods.

Moreover, different goals can be distinguished that are not necessarily all present in a particular backcasting project. Possible goals for backcasting studies include (Quist et al. 2006):

- Generating normative alternatives for the future and analyzing their opportunities, potentials, environmental benefits, and other effects
- Putting attractive normative scenarios on the agenda of relevant societal arenas
- A follow-up agenda containing activities or actions for the different stakeholders involved in, or contributing to, bringing about the desirable future and its implementation
- Stakeholder learning with respect to the alternatives, the effects, and the opinions of other stakeholders
- Stakeholder support in regards to vision, design, analysis, and commitment to the follow-up agenda.

In sum, the key components of the participatory backcasting include (Quist 2002; Quist and Vergragt 2006):

(1) The construction and use of desirable normative scenarios and goals;
(2) Broad stakeholder participation and stakeholder learning (on the level of paradigms and values); and
(3) Combining process, participation, analysis, and design using a wide range of methods within the overall backcasting approach.

The participatory backcasting approach uses a set of questions for each step. Table 11.3 illustrates these questions in a backcasting project where step 4 “Elaboration and defining action–agenda and follow–up” and step 5 “Embedding and initiating or stimulating follow–up activities” are combined due to limited time and changes in stakeholder involvement. Specifically, as suggested by Quist et al. 2006, p. 872). “implementation and embedding is changed into making a follow–up

Table 11.3 Guiding questions for each step in the backcasting study

Questions for backcasting steps	Methods and tools
Step 1: Strategic problem orientation What is the (socio-technical) system to be studied? Which societal needs/functions are addressed by this system? What are important trends and development related to this system/needs? What are major sustainability problems and what are the causes? How is the problem defined and what are the possible problem perceptions? Who are stakeholders and what are their opinions concerning sustainability problems and possible solutions?	Problem analysis; actor/stakeholder analysis; system analysis; modeling methods; interactive methods
Step 2: Generating sustainable future visions What are the demands (terms of reference) for the future vision? How does the future sustainable socio-technical system and need fulfillment look like? Which sustainability problems have been solved? Which technologies have been used in the future vision? How are culture and the social and economic structure different? How do people live in the future vision? How can it be made more sustainable and more attractive?	Creativity methods; design methods; interactive methods; modeling methods; visualization methods
Step 3: Backcasting analysis What technological changes are necessary for achieving the future vision? What cultural and behavioral changes are necessary? What structural, institutional and regulatory changes are necessary? How have necessary changes been realized and what stakeholder (groups) are necessary? Is it possible to define milestones for the identified technological, cultural and structural changes when looking back from the vision?	Backcasting analysis
Step 4: Elaboration, design, analysis and defining follow-up agenda What is a more detailed design of the socio-technical system in the future vision? What are the results of different analyses (social, consumer, environmental, economic, etc.)? What are drivers, barriers and conditions for the achieving the future vision? What could different stakeholder groups (research, government, companies, public interest) do and what should be on the action agenda? Which activities can be started now and who should do them? Elaborate a specific follow-up proposal that contributes to the system change and define who should contribute and what should be contributed?	Design methods; analytical methods such as impact assessment and technology assessment; planning methods

Source Quist et al. (2006)

proposal, sketching a rough development and implementation trajectory and analyzing what could or should be the contribution of different stakeholder groups."

11.5 A Synthesized Scholarly and Planning Approach to Strategic Smart Sustainable City Development

11.5.1 Premises and Assumptions Underlying the Synthesis

The synthesized scholarly methodology and planning approach to strategic smart sustainable city development is primarily intended to be used by researchers and scholars working within academia and research institutes, who are particularly concerned with the investigation and analysis of strategic smart sustainable city development as part of futures studies. In a nutshell, it is to be applied in the academic context. The synthesis is based on the premise that while backcasting approaches or methodologies do differ in their steps and thus guiding questions, they do converge on the essentials. For example, most of the applied backcasting approaches include construction of the future vision and backcasting analysis. These must accordingly be included in the proposed scholarly and planning approach to strategic smart sustainable city development, with a slight difference brought to the guiding questions in accordance with the topic (see Table 11.4). In addition, the proposed approach is based on one normative vision. The backcasting approach is traditionally based on one normative vision, but multiple visions can also be used to explore different future alternatives (Tuominent et al. 2014). Such vision is prescriptive by focusing on what a smart sustainable city should be. As such, it aids researchers and scholars in clarifying shared values and preferences in terms of sustainability so they can develop visions of desirable (sustainable) futures. Indeed, it allows them to understand what they would prefer the future to be and then take the appropriate (or necessary) steps to create that preferred future. Furthermore, smart sustainable city development integrates and fuses sustainable development, technological development, and city development, forming an interdisciplinary and transdisciplinary area. Bibri (2018) endeavors to systematize the very complex and dense scientific area of smart sustainable cities in terms of identifying, distilling, and structuring the core dimensions of a foundational framework for smart sustainable city development as a set of future practices. The purpose is to set a framework that analytically relates city development, sustainable development, and technology development. One implication of this is that a more appropriate backcasting methodology and planning approach to strategic smart sustainable city development should draw on insights (steps and guiding questions) from diverse methodologies or approaches in ways that embrace the three constituting strands of the development in question.

Table 11.4 Steps and guiding questions of backcasting methodology and planning approach

Steps and guiding questions of backcasting methodology and planning approach
Step 1: Defining normative assumptions and setting criteria and goals in relation to urban sustainability What are the objectives with a description of the aim of the analysis in terms of its urban, environmental, socioeconomic, and technological scope? What specific sustainability and smartness goals are the objectives translated to for scenario analysis? How should sustainability and smartness goals be integrated and complement each other in city development?
Step 2: Describing the current situation, prevailing trends, and expected developments What are important global trends and developments related to city development? What are major urban sustainability problems and what are the causes and challenges? Are the current situation, prevailing trends, and expected developments evaluated against the goals? Which urban systems or domains are to be targeted?
Step 3: Constructing an image of the future for smart sustainable city What are the demands (terms of reference) for the future vision? How does the future smart sustainable city look like? Which sustainability problems and challenges have been solved by achieving the goals? Which technologies and their applications have been used in the future vision?
Step 4: Backcasting Analysis What technological and urban changes are necessary for achieving the future vision? What institutional, organizational, and regulatory changes are necessary? How have necessary changes been realized and what stakeholders are necessary?
Step 5: Elaboration and Implementation What are the results of environmental and socioeconomic analyses in relation to urban sustainability? How consistent are they with the specified goals and vision outcomes? What political actions and institutional responses (city government, regulatory body, industry, research community, etc.) are required for the implementation of the vision and the policy measures implied in those actions and responses? What should be on the action agenda?

The key assumptions underlying this backcasting and planning approach include the following:

- Efficient utilization and conservation of land resources;
- Decreasing energy usage through advanced ICT applications;
- Integrating renewable and energy efficiency technologies/solutions;
- Mitigating environmental impacts (GHG emissions and waste);
- Promoting sustainable transportation;
- Safeguarding biodiversity and ecosystem;
- Coevolution of technology and city;
- Goal-oriented;
- Design-oriented;
- Research-oriented;
- Policy-oriented; and
- Time horizon of 25 years.

11.5.2 The Outcome of the Synthesis

The intent of the above premises and assumptions is to provide the rationale for synthesizing the scholarly methodology and planning approach, which can be used to investigate and analyze the development of smart sustainable cities. Yet the researchers and scholars' worldview and aim are the most important criteria that determine how futures studies on smart sustainable city development can be developed and conducted in terms of the details of the guiding questions. Futures studies dealing with the development of future models for smart sustainable city can adopt backcasting as a scholarly methodology or planning approach to help identify and implement strategic decisions associated with urban sustainability. An example of a scholarly endeavor in this regard would be to investigate and analyze how to strategically assess, improve, and sustain the contribution of an integrated model of the most sustainably sound urban forms to the goals of sustainable development toward achieving sustainability—with support of ICT of pervasive computing in terms of its innovative solutions and sophisticated methods offered by smart city approaches—under what is labeled "smart sustainable cities" of the future (see Bibri 2018 for a detailed overview). This research endeavor involves determining the most strategic steps to be taken to achieve smart sustainable cities as a vision of success or a desirable future.

However, the synthesis of the proposed scholarly and planning approach (see Table 11.4) is based on the findings and insights drawn from the review and discussion of various backcasting approaches (namely Akerman and Höjer 2006; Höjer and Mattsson 2000; Carlsson-Kanyamaa et al. 2003; Holmberg 1998; Holmberg and Robèrt 2000; Quist et al. 2006; Quist and Vergragt 2006; Phdungsilp 2011; Robinson 1990; Robert et al. 2002; Weaver et al. 2000). It is further illustrated and supported by the case studies presented and described in the next section.

11.6 Case Studies

11.6.1 The Project Gothenburg 2050

11.6.1.1 Overview of the Project Gothenburg 2050

As a research endeavor concerned with long-term sustainable images of the future to increase the potential of reaching a sustainable world, the Project Gothenburg 2050 aims to draw up and develop long-term visions for the sustainable city in Sweden that as part of a sustainable society could motivate a faster development toward sustainability. The project specifies energy and environment targets as part of a sustainable society with the principle of equity. The population in the city is estimated to be 1.2 million and the assumption is made that people live a pleasant life (Phdungsilp 2011). The objective of the project is to develop, compile, and disseminate knowledge of what a sustainable society could look like and to stimulate research about long-term development. The intent of the project is to provide a basis for municipal and regional planning as well as strategic development. The images of the future for sustainable city will result in the implementation of different demonstrations and pilot projects, and knowledge and research results are brought out to both societal actors and the public. The project has initiated research, development, and demonstration endeavors involving a wide variety of stakeholders to discuss various aspects of the concept of a sustainable future and to participate in developing desirable future scenarios (Phdungsilp 2011). The project was carried out in cooperation between different universities, energy companies, city government, public administration, and research councils. The use of visions of a long-term future was an important tool for developing long-term strategies of a future city and surrounding regions. Like most backcasting approaches used in futures studies dealing with urban sustainability, backcasting is in this project concerned with the preferable (what we would prefer to happen in the future), and then explores strategies for achieving the sought goals with the knowledge of today about how the future could be. The backcasting process used in this project is based on the amalgamation of Robinson's (1990) approach and the TNS framework (Holmberg and Robèrt 2000). In addition to being active in a number of planning processes, the project provides visionary and sustainability focused input into the development of a new urban energy plan, sustainable transportation, urban planning, and water and waste management planning (Phdungsilp 2011).

11.6.1.2 City Foresight Methodology Used in the Project Gothenburg 2050

The methodology used in the Project Gothenburg 2050 consists of four steps, namely (Phdungsilp 2011):

1. Description of the present and trend analysis;
2. Setting criteria and goals (sustainability);
3. Developing images of the future; and
4. Analysis of how to reach the images.

The overall picture of the planning methodology is illustrated in Fig. 11.2. The first step aims to identify the problem and to describe the present situation. Existing trends addressed include energy systems, transportation, urban structure, eco-cycling, and food. The second step defines criteria, sets goals, and identifies limitations for the study, with consideration of a set of external factors that might affect the scenario. The third step constructs one or several alternative images of the future based on the criteria and goals chosen in the second step, indicating a solution to a major problem. The fourth step analyzes the possibilities to reach the society described in the alternative images.

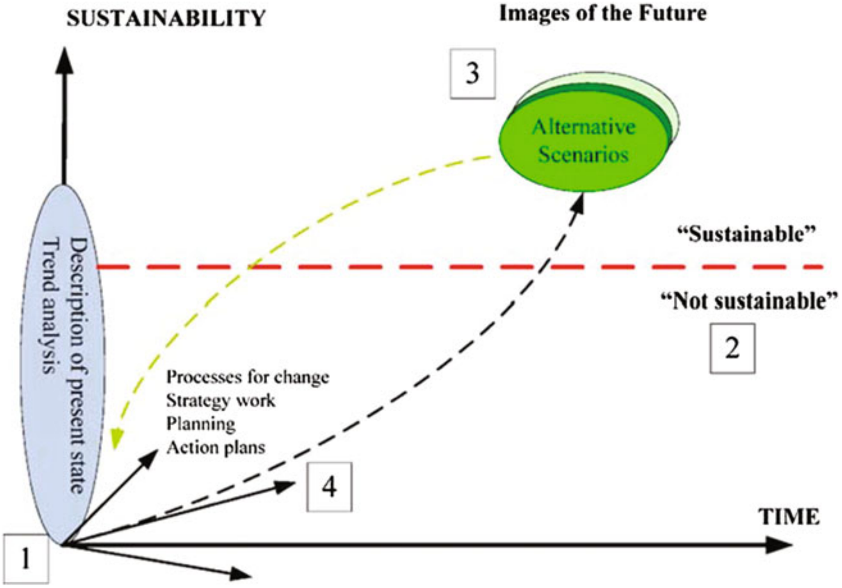

Fig. 11.2 The city foresight methodology used in the Project Gothenburg 2050. *Source* Phdungsilp (2011)

The remaining part of this subsection presents different visions and scenarios in the Project Gothenburg 2050 pertaining to sustainable energy, transport system, urban design, water and waste management, and food and grocery chain. Worth noting is that sustainable city development is likely to involve different domains than these, as well as different aspects, depending on the social, cultural, economic, and political factors shaping the socio-technical landscape where the city is embedded as an amalgam of innovation systems. However, the visions and images were developed for strategic planning, following the definition of the criteria for sustainability and an analysis of the present state and trends in the relevant domains. Images of the future were developed based on a participatory approach, visualized using workshops and other inputs, compared to the present state and trends, and used for the planning process.

The sustainable energy system is a combination of smart and efficient use of energy, renewable energy supply (from biomass, wind, hydropower, solar electricity, etc.), changing lifestyle, energy-efficient urban planning, and energy storage in a hydrogen society. The energy supply was envisioned to be reduced by one-third: each person will use about 25,000 kWh. The sustainable transport system is reliant on its closeness to daily activities to facilitate short-range trips and reduce travel needs, high accessibility, purpose-oriented, and energy-efficient vehicles in pools, fewer, and more fully loaded goods transportation, and fuel from the sun. This scenario shows that it is possible to decrease the energy use for transportation by almost 75% per capita due mainly to a reduction in short distant personal transportation. The sustainable urban design emphasizes compact city features: density, diversity, mixed land use, energy-efficient buildings, closeness to transportation nodes and local squares, in addition to new rail systems and more space for bike and pedestrians as well as green areas. As to eco-cycling, it is concerned with waste management and sustainable water to significantly decrease the amount of waste through long-lasting products adapted to the ecosystem, reuse of products and material recycling, a clean and visible water environment, and few but safe final repositories. The scenario for a sustainable eco-cycle society shows that it is possible to half the total amount of waste compared with today, while unsorted mixed waste is envisioned to decrease by 70% compared to the total amount of waste today. The decrease in total amount of waste is a result of dematerialization, repair and reuse, durable product use, and lifestyle changes. The sustainable food and grocery chain focuses on working with sustainable and locally produced food, a diet with a higher proportion of vegetables, closeness between producers and consumers, food trade based in local squares, and conscious and energy-efficient consumption. The envisioned decrease concerns animal protein consumption as well as junk food and drinks.

11.6.2 Ph.D. Project: A Novel Model for Smart Sustainable City

The synthesized scholarly and planning approach to strategic smart sustainable city is to be used in an ongoing Ph.D. project (see Bibri 2018 for further details) at the Norwegian University of Science and Technology, Trondheim, Norway. The core focus of this scholarly research endeavor is on how to strategically advance and sustain the contribution of an integrated model of the most sustainably sound urban forms to the goals of sustainable development toward achieving sustainability—with the support of ICT of pervasive computing in terms of its innovative solutions and sophisticated methods being offered by smarter cities as future forms of smart cities—under what is labeled "smart sustainable cities" of the future (see Bibri and Krogstie (2017a) for an extensive interdisciplinary literature review).

11.6.2.1 The Applied Theoretical Approach to the Ph.D. Project

The extensive interdisciplinary literature review conducted by Bibri and Krogstie (2017a) shows that critical issues remain unsettled, less explored, and theoretically underdeveloped for applied purposes concerning the existing models of sustainable urban form as to their contribution to sustainability with respect to the use and application of ICT of pervasive computing. Accordingly, the main conclusion of this review is that the applied theoretical inquiry into smart sustainable cities of the future is deemed of high pertinence and importance—given that the research in the field is still in its early stages, and hence ought to be grounded in a more theoretically and practically focused approach to avoid any ad hoc progress in the field, and that the subject matter draws upon influential theories and established academic disciplines and discourses with practical applications and wide-ranging implications. The significance of the applied theoretical inquiry in the field of smart sustainable cities provides a strong motivation for the kind of research being pursued: the development of a novel model for smart sustainable city. Opting for this inquiry approach is moreover deemed timely given the diffusion of sustainability, the rise of ICT, and the spread of urbanization as important global shifts at play in the world. In addition, it is academically worthy to engage in a scholarly research endeavor that lies at the interface of topical subjects, i.e., subjects of immediate relevance due to their relation to current urban phenomena. In light of the above, the review suggests the development of a framework integrating smart cities and sustainable cities to align the existing problems and solutions identification for future practices in the domain of urban planning and development. Specifically, this framework involves how sustainable urban forms can be better monitored, understood, analyzed, and planned using ICT of pervasive computing to strategically advance and sustain their contribution to sustainability. This is anchored in the underlying assumption that future ICT as a set of enabling, integrative, and constitutive technologies and their novel applications pertaining to big data analytics and context-aware computing can make substantial contributions in this regard—not only in terms of enhancing the operational functioning of sustainable urban forms, but also in terms of their planning with regard to management, administration, development, and governance (Bibri 2018). Currently, one of the most significant intellectual challenges identified in the field of sustainable cities lies in producing a theoretically and practically convincing model of sustainable urban form with specified and clear components—as well as augmented with advanced technologies and their novel applications and sophisticated methods in a bid to enhance the contribution of the underlying typologies and design concepts to the goals of sustainable development (Bibri and Krogstie 2017a, b).

It is worth mentioning that the Ph.D. project has a propensity to emphasize a mix of coherent and scalable typologies and design concepts alongside data-driven and context-aware environmental, management, and governance systems. The intention is to avoid looking for one-rule model with a determined set of smart solutions. The rationale is that it is potentially valid to argue for several pathways, possibilities, combinations, and futures when it comes to smart sustainable cities. Hence, the Ph.D. project departs from the perspective that there is no one single optimal or ideal smart sustainable urban form but diverse alternative forms whose discussion should normally follow a more heuristic trajectory, addressing a plurality of important issues and methods, rather than producing one-rule models, one-liners or optimal solutions. Important to note, indeed, is that smart sustainable urban forms may differ as to their contribution to the goals of sustainable development. Different planners and scholars together with ICT experts may develop different combinations of design and planning concepts together with advanced technologies and their applications to achieve the goals of sustainable development. They might come with different forms, where each form emphasizes different concepts and technologies.

11.6.2.2 On the Foundational Framework for Smart Sustainable City Development

In light of the above, it is deemed of high significance to devise a multidimensional foundational framework consisting of relevant theories and academic disciplines and discourses that underpin the development of smart sustainable cities as a set of future practices (see Bibri 2018 for a detailed account of such framework). This framework emphasizes the interdisciplinary and transdisciplinary nature and orientation of the topic of smart sustainable cities and thus the relevance of pursuing an interdisciplinary and transdisciplinary approach into studying this topic. The endeavor is to systematize the very complex and dense scientific area of smart sustainable cities in terms of identifying, distilling, and structuring the theoretical, disciplinary, and discursive dimensions of the framework for smart sustainable city development. The aim is to set a framework that analytically relates city development, sustainable development, and technology development, while emphasizing how and to what extent sustainability and ICT have particularly become influential in city development in modern society. Indeed, in the subject of smart sustainable city development, the underlying theories and academic disciplines and discourses and their integration are a foundation for action. In other words, the theoretical, disciplinary, and discursive dimensions of the foundational framework have strong implications for smart sustainable city development. The synergic interaction between these dimensions produces a combined effect greater than the sum of their separate effects. This implies that this multidimensional framework has a supporting, underpinning, and shaping role in smart sustainable urban development. As such, it justifies and underlies the applied theoretical approach to the Ph.D. project being undertaken, which aims to develop a novel model for smart sustainable city using a backcasting approach to planning, where the focus is on the application of a set of integrative theories and academic disciplines and discourses. In particular, the theories of sustainability and ICT have become influential and prevalent in many aspects of urban life, whether in the built environment, urban systems, urban domains, urban services, or urban forms. The Ph.D. project focuses specifically on how sustainability can be integrated with ICT in their application to urban forms (design and planning of smart sustainable cities), and how this functions and is useful in an increasingly computerized and urbanized world. This theoretical integration is therefore of paramount importance as to how the subject of smart sustainable city development should be studied and applied. In other words, how sustainability and ICT theories are applied in the real world, how they work and how useful they are, constitute relevant subjects for the Ph.D. project being conducted in the area of smart sustainable cities. There are many theories that are influential in how the subject of smart sustainable city development is studied and applied. There are some theories that may be strongly based on scientific evidence that would need expert knowledge to challenge, and others that are more philosophical and institutional and thus more open to general critical examination. What the implications of the integrated theories in this scholarly research are and whether such theories deliver what is claimed can be studied by examining actual case studies (city projects, programs, strategies, and future plans). In this way, theoretical issues and their effects are of primary focus in the Ph.D. project. This kind of research combines investigation (case studies) and understanding of theory—a literature-based activity in conjunction with consultations with influential thinkers and experts in the field, to study the application and effects of theories. The Ph.D. project thus involves an interesting and varied set of activities that are suitable for combining thinking with doing. Indeed, with its strong applied focus, it is not alienated or divorced from real life; rather, it is to be carried out to inform the planning and design of smart sustainable cities as a holistic urban development strategy. In all, what underpins and motivates the pursuit of the applied theoretical approach is that the Ph.D. project is profoundly theoretically integrated yet under-researched, empirically underdeveloped, and inherently inductive. In addition, all institutionalized and socially anchored actions are grounded in some kind of theories and academic disciplines and discourses.

11.6.2.3 Explicit Research Goals

The Ph.D. project addressing the topic of smart sustainable city development falls within the broad research field of sustainability transition and sustainability science where ICT is seen as a salient factor given its transformational, disruptive, and synergetic effects as an enabling, integrative, and constitutive technology. In light of this, the approach to the Ph.D. project is of an applied theoretical kind, and its aim is to investigate and analyze how to advance and sustain the contribution of sustainable urban forms to the goals of sustainable development with support of ICT of pervasive computing. This is to primarily devise a novel model for smart sustainable city based on scientific principles, theories, and academic disciplines and discourses used to guide urban actors in their practice toward sustainability and analyze its impact. This involves the application of a set of integrative foundational elements drawn from urban planning, urban design, sustainable development, sustainability science, data science, computer science, complexity science, systems theory, systems thinking, and ICT. The proposed framework merges the physical and informational landscapes of smart sustainable cities for the sheer purpose of advancing sustainability. The main focus is on amalgamating the design and planning principles of an integrated model of the most sustainably sound urban forms with the smart solutions and sophisticated approaches pertaining to ICT of pervasive computing for sustainability—based on big data analytics and context-aware computing technologies and their novel applications. These span a range of urban systems and domains in terms of operations, functions, services, designs, and policies. The underlying assumption is that ICT of pervasive computing will result in a blend of smart applications enabled by constellations of instruments across many spatial scales linked via multiple networks for providing continuous data flowing from various urban systems and domains (processes, activities, movements, interactions, observations, etc.), which can provide a fertile environment conducive to advancing the contribution of sustainable urban forms to sustainability over the long run by monitoring, understanding, analyzing, and planning them in ways that strategically improve and sustain this contribution through the design and planning principles of sustainability.

The primary intention is to produce a theoretically and practically convincing model for smart sustainable city of the future, which combines the strengths of both smart cities and sustainable cities. And the intent of developing this model is to address the deficiencies and misunderstandings pertaining to smart cities with respect to incorporating the goals of sustainable development, as well as the limitations, uncertainties, and fallacies concerning sustainable cities with regard to translating sustainability into the built form and evaluating the extent to which they contribute to the goals of sustainable development. This research endeavor involves determining the most strategic steps to be taken to achieve smart sustainable cities as a vision of success or a desirable future. Hence, an appropriate response to this approach to smart sustainable city development involves the analysis of several factors, including past, present, and future situations; long-term visions; formulation, implementation, and follow-up; transfer and deployment of technologies; building and enhancement of human and social capacity; and regulatory policies. These factors are intertwined and thus cannot be isolated from each other in all endeavors of urban sustainability, which indeed postulates a system-oriented perspective to addressing environmental, economic and social issues.

11.6.2.4 Contribution and Significance

The Ph.D. project contributes toward creating new and also advancing knowledge in the field of sustainable cities and smart cities by doing an innovative research on smart sustainable cities of the future. In specific terms, it advances sustainable urban forms through ICT of pervasive computing given the underlying potential for improving urban operations, functions, designs, services, policies, and other practices in terms of automation, control, optimization, management, planning, and governance in line with the goals of sustainable development.

By taking on the line of the applied theoretical inquiry and achieving the explicit research goals, the Ph.D. project will contribute to the scientific literature on smart sustainable cities in several ways, as well as to urban planning and development practices. It will be a significant endeavor as to improving the contribution of sustainable urban forms to the goals of sustainable development by producing a theoretically and practically convincing model of smart sustainable urban form—with clear components and their integration, along with the necessary regulatory and institutional changes. This could result in a groundbreaking framework that will bring a whole new dimension to sustainability in an increasing computerized and urbanized world. Indeed, the proposed model of smart sustainable urban form as a new urban construct is intended to be presented to the world, something to break through to the mainstream and to be replicated in major cities of the globe, especially within ecologically and technologically advanced nations. Hence, the quest is to create a model that can boost institutionalized urban practices and new forms of urban policy analysis and planning at the national and international levels in the context of sustainability. Especially, this model is intended to be used for, in addition to city development, benchmarking, assessing, and ranking emerging smart cities and sustainable cities in terms of how they embrace and integrate the foundations of each other to advance sustainability toward a more holistic urban development approach. In addition, this model will be best applicable to cities or districts badgering or regenerating themselves as smart sustainable, as well as to cities or districts yet to be developed. All in all, this model is believed to be the first of its kind and hence has, to the best of one's knowledge, not been produced elsewhere. Accordingly, it will pave the way for large-scale and more focused investigations within the domain of smart sustainable urban development and its future form. It will moreover provide a form of grounding for deep discussions to debate over the point that future ICT embodies a morphing power in that it alters how cities evolve as well as reshape and create new urban realities given its disruptive, substantive, and synergetic effects, particularly on forms of urban operational functioning, management, planning, development, and governance that are required for future forms of sustainability in emerging and future cities.

11.7 Backcasting as a Useful Tool for Achieving Urban Sustainability: The Shaping Role of Political Action in Sustainability Transitions

To move cities toward sustainability, policy actions should be fostered through relevant principles and values, and the environmental, social, and economic impacts associated with sustainability need to be anticipated and assessed. Being normative, backcasting is a suitable and useful framework for supporting policymakers and facilitating and guiding their actions to reach sustainability transitions. The choice of such framework to develop scenarios of smart sustainable cities is supported by its appropriateness to reach the policy targets (sustainable development goals) in tandem with societal and economic development. Also, scenarios based on backcasting may be capable of generating new policy directions needed if cities are to become smart sustainable (see OECD 2002 for guidelines toward environmentally sustainable transportation). The application of a backcasting approach assumes a vision of an evolutionary process of policy with a time frame of a generation (30 years), which is a basic principle to allow the policy actions to pursue the path toward smart sustainable cities as a sustainable transition. The backcasts of different alternative futures are intended to reveal the relative implications of different policy targets (see Robinson 1982), as well as to determine the opportunities for policymaking.

It is important to recognize the interplay between smart sustainable cities and other scales, as well as the links to political processes on a macro level, e.g., regulatory policies and governance arrangements (Bibri and Krogstie 2016). To include macro processes of political regulation is central for the backcasting approach. One of the key actors involved in sustainability transition governance is government in terms of political mechanisms in the form of funding schemes, research management (regulation of public research institutes), innovation and technology policies, regulatory standards, market manipulations by the state, public–private collaborations and partnerships, and so on (Bibri 2015b). In this respect, government generates top-down pressure from regulation and policy and the use of market and other forms of incentives, while promoting, spurring, and stimulating the collective learning mechanisms by supporting innovation financially and providing access to the needed knowledge (Rotmans et al. 2001).

The act of regulating entails a set of principles, rules, or laws designed to govern urban behavior in terms of development by carrying out legislations. Regulating city development through policies is the responsibility of many different government departments and agencies. In other words, regulations are issued and enforced by various regulatory bodies formed or mandated to carry out the provision or the intent of legislations. A city government affects urban development through regulatory policies, which aims to promote sustainability efforts. Most city governments have some regulations covering a variety of urban areas, including transport, traffic, mobility, environment, energy, land use, health, education, and safety in the context of sustainability.

In discursive terms, political action is of critical importance to the emergence, insertion, functioning, and evolution of smart sustainable cities as a new techno-urban discourse and an amalgam of innovation systems (Bibri and Krogstie 2016). Indeed, political practice is at the core of the theory of discourse (e.g., Foucault 1972) and the theoretical framework of innovation system (e.g., Chaminade and Edquist 2010; Kemp 1997; Kemp and Rotmans 2005; Rånge and Sandberg 2015) in terms of the shaping role of political mechanisms in the production and evolution of discourses and socio-technical systems governing technological innovations, respectively. Recommendations for smart sustainable cities as a drastic techno-urban transformation, which entail a set of intertwined socio-technical systems and a cluster of interrelated discourses embedded in the wider socio-technical landscape, are unlikely to proceed without parallel political actions. Drastic shifts to sustainable technological regimes “entail concomitantly radical changes to the socio-technical landscape of politics, institutions, the economy, and social values” (Smith 2003, p. 131). From a discursive perspective, political processes are at the heart of material mechanisms and practices in terms of translating the vision of smart sustainable cities into concrete projects and strategies and their institutionalization in urban structures and practices (Bibri and Krogstie 2016). And from an innovation system perspective, political processes represent the setup under which dynamic networks of urban actors and entities can interact within diverse industrial sectors in the development, diffusion, and utilization of knowledge and technology pertaining to sustainable urban development.

Smart sustainable cities as an urban transformation have a quite strong governmental and policy support, particularly within ecologically and technologically advanced societies (Bibri and Krogstie 2016). The underlying idea figures in many policy documents and agenda as well as political statements and argumentations, in addition to being used by many organizations and institutions (e.g., industries, universities, research institutes, etc.). It is not an element closed in the "ivory tower" of research community, but it is influenced by the macro-political practices in connection with sustainable development and ICT innovation (Bibri and Krogstie 2016). This is anchored in the premise that drastic urban shifts are unlikely to proceed without parallel political action, to reiterate. As a corollary of its dynamic interaction with new discourses, politics forces their emergence, functioning, and evolution (Foucault 1972).

However, the number of methods and tools to develop sustainability and operationalize sustainable development has, over the past two decades, grown rapidly. The complexity of planning for sustainability has emphasized the importance of applying the backcasting approach to have an informed vision of specific goals so as to strategically deal with potential trade-off among different decisions and actions, as current trends, actions, and plans are usually part of problem (Robert et al. 2002). The prominence of backcasting as a form of strategic thinking and problem-solving framework lies in that it focuses on the long-term consequences and problems of the present decisions and actions based on the discussion of various alternatives from a sustainability perspective. Sustainability takes into account that current trends should only influence the initial scale of the transition (e.g., smart sustainable cities), not its direction, which is the epitome of backcasting. Grounded in holistic thinking, sustainability is based on the idea of consciously and incessantly going with the grain of nature and providing the conditions for deploying the frameworks necessary for its operationalization and its translation into practices in a more dynamically innovative way in order to reach a sustainable society. As such, it is based on an all-embracing understanding of the complex challenges and mounting problems facing society, which is necessary for making all-inclusive decisions and taking well-informed actions for its long-term benefit, thereby the relevance of applying the backcasting approach. Yet, the backcasting approach should be complemented by the more commonly applied forecasting approach. If forecasting is the sole planning strategy, there are substantial risks that "fixing the problem" will retain the principle mechanisms from which that problem originates in the first place (Miola 2008). In other words, forecasting is unlikely to generate solutions that presuppose the breaking of trends, which may pose an issue for planning in the long run due to the discontinuities that are most likely to emerge or occur. In relation to this argument, Dreborg (1996) underscores that the way we perceive the possible or reasonable may be a major obstacle to a real change.

To achieve sustainability goals requires an amalgamation of technological, social, cultural, political, institutional, and organizational changes that are to affect and shape the actions of many stakeholders when they are diffused into or permeate society. Such changes involve a complex process of transformation on the long term, especially in the context of smart sustainable cities which are very complex due to the inherent uncertainty of the future, the inherent dynamically changing nature of urban environment, and the inherent ambiguity of stakeholders having different and sometimes conflicting value sets. Planning for urban sustainability requires novel methods and paradigms as alternative approaches to traditional planning (see Rotmans et al. 2000). This is predicated on the assumption that it is necessary to understand the possible linkages among environmental, socioeconomic, and institutional processes. Similarly, any resultant solution from backcasting would broadly affect many stakeholders across a multitude of societal dimensions, such as technological, social, cultural, institutional, political, and organizational.

Smart sustainable cities represent a strategic development process of working toward a balance of environmental, economic, and social goals, an approach to conciliating the continuity of—rather conflicting, competing, and sometimes contradictory—forces. Conflicts among the goals of sustainable urban development to achieve the long-term goals of urban sustainability are challenging to deal with and daunting to overcome (Bibri and Krogstie 2016, 2017a). This has indeed been, and continues to be, one of the toughest challenges facing urban scholars and planners as to decision-making processes in the realm of sustainable cities (Bibri and Krogstie 2017b) as well as smart cities due to the multidimensional risks they pose to environmental sustainability (see Bibri and Krogstie (2016) for an overview). Despite sustainable urban development seeking to provide an enticing, holistic approach to evading the conflicts among its goals, these conflicts “cannot be shaken off so easily”, as they “go to the historic core of planning and are a leitmotif in the contemporary battles in our cities”, rather than being “merely conceptual, among the abstract notions of ecological, economic, and political logic” (Campbell 1996, p. 296). Even if these goals coexist uneasily in contemporary cities, sustainable urban development as a long-range objective for achieving the goals of urban sustainability is worthy for urban planners since they need a strategic process to achieve the status of sustainable cities, to increase the contribution of smart cities to sustainability, and to stimulate the development of smart sustainable cites. As expressed by Campbell (1996, p. 9), planners will in the upcoming years “confront deep-seated conflicts among economic, social, and environmental interests that cannot be wished away through admittedly appealing images of a community in harmony with nature. Nevertheless, one can diffuse the conflict, and find ways to avert its more destructive fall-out.” To put it differently, sustainable urban development advocates can—and ought to—seek ways to make the most of all three value sets at once. This is in contrast to keeping on playing them off against one another. With that in mind, the synergistic and substantive effects of sustainable development on forms of urban planning and development require cooperative effort, collaborative work, and concerted action from diverse urban stakeholders in order to take a holistic view of the complex challenges and pressing issues facing contemporary cities (Bibri and Krogstie 2017a). In all, sustainable development is a continuously unfolding but strategic pathway for change centered on bringing environmental, economic, and social considerations to the core of our understanding of social and human development. Potentially, this involves the reconfiguration of economic and societal activities within prominent sectors based on an all-embracing understanding of the problems facing society. This is necessary for making all-inclusive decisions and taking well-informed actions for the long-term benefit of society. This implies in the context of smart sustainable cities the integration of environmental information with physical, economic, social, and technological dimensions in decision-making and planning processes.

11.8 System Thinking and Backcasting

Smart sustainable cities are complex systems par excellence. This is manifested in a variety of ways to think of the underlying subsystems as connected and joined together by a web of relationships that interact to produce collective behavior that cannot easily be explained in terms of interactions between the individual constituent elements. Bibri and Krogstie (2017a) conceive of smart sustainable cities as a social fabric made of a complex set of networks of relations between various synergistic clusters of urban entities that, in taking a holistic perspective converge on a common approach to using and applying smart technologies to create, develop, disseminate, and mainstream innovative solutions and sophisticated methods that help provide a fertile environment conducive to advancing sustainability by strategically assessing and continuously enhancing the contribution to the goals of sustainable development. As such, they are inherently intricate and dynamically changing through the very technologies being used to monitor, understand, and analyze their underlying physical structures, spatial and temporal scales, urban services, and urban processes associated with management, planning, and development to improve their sustainability performance and thus increase their ability to confront urbanization and mitigate its multidimensional effects.

Therefore, smart sustainable cities involve special conundrums, intractable problems, and complex challenges pertaining to sustainability and urbanization. It follows that to tackle or deal with such systems requires newfangled ways founded on more innovative solutions and sophisticated approaches with respect to how cities can be monitored, understood, analyzed, managed, planned, and developed. This in turn must be based on systems thinking and complex systems approach into explaining, understanding, and dealing with smart sustainable cities so as to enable more effective actions necessary for enhancing their functioning and adaptation and thereby guiding their development toward sustainability. The underlying assumption is that systems thinking and complexity science are integral to the understanding of smart sustainable cities, which is a moving target in that they are becoming more complex through the very technologies being used to understand them. Meadows and Wright (2012) state that “as our world continues to change rapidly and become more complex, systems thinking will help us manage, adapt, and see the wide range of choices we have before us. It is a way of thinking that gives us the freedom to identify root causes of problems and see new opportunities.” Especially, some of our solutions have created further problems, and many complex problems have been solved by focusing on external factors because they are embedded in larger systems. As real messes, the problems rooted in the internal structure of complex systems as well as their interaction with their environment (e.g., pollution, environmental degradation, toxic waste, economic instability, social inequality, unemployment, and chronic disease) have been difficult to deal with and refused to go away. They persist despite the analytical ability, technical intelligence, and human brilliance that have been directed toward circumventing and eradicating them. They persist because they constitute intrinsically systems problems—undesirable patterns of behavior characteristic of the system structures and reciprocal relationships resulting from the profound interactions that produce them. They will yield only as we reclaim our holistic thinking as well as intuition and thus see the whole system as the source of its own problems, and find the astuteness and wisdom to restructure it and reshape its interaction.

The system perspective on smart sustainable cities can be shown in two ways. On one hand, the focus should be on a broad range of impacts, including the following:

Environmental impacts in terms of provisioning services, regulating services, cultural services, supporting services, and diseases and hazards.
Economic and social impacts in terms of goods, services, resource extraction, and stress.
Human well-being in terms of material needs, health, security, and freedom of choice.

On the other hand, the focus should be on the network of processes in the urban activities pertaining to production and consumption patterns. The system perspective brings into view the net impacts of a city system as a whole. System analysis aims to determine the overall environmental, economic, and social impacts of urban processes and activities across various urban domains. This broad scope means that systems can be defined in quite different ways, depending on how the processes and activities are connected with each other. There is a real need for a shift from an "end-of-pipe" philosophy of environmental protection toward a new paradigm in which environmental considerations encompass the full social and economic structure as to the production and consumption of natural resources. This has profound implications for city government and urbanites, and aid in avoiding what has tended to prevail for decades before the inception of sustainable development: shifting problems from one urban domain to another or from one environmental issue to another. The goal of smart sustainable cities requires a paradigm shift in city governments, organizations, and citizens. It requires responsible environmental management, technological innovations, and behavioral change.

Scenario planning as part of the backcasting approach may involve aspects of systems thinking. For example, it is important to recognize that many factors may intertwine in complex ways to create sometimes unexpected futures (due to nonlinear relationships in that a small perturbation may cause a large effect or nonlinear behavior over time based on feedback loops) (Bibri 2018). The backcasting approach also allows the inclusion of factors that are difficult to formalize, including unprecedented regulations, deep shifts in social values and political beliefs, the shifting nature of environmental politics, radical shifts in institutions, ecological modernization of mind, and novel insights about the future. Backcasting planning can be integrated with systems thinking approach in scenario development to bring some dynamic nature to the process of planning. Systems thinking used in conjunction with backcasting planning leads to desired futures in the form of scenarios because the causal relationship between the intertwined factors can be demonstrated. In fact, an important goal of backcasting is to raise awareness of the necessity of long-term and system thinking alongside an integral multidisciplinary approach, a focus on societal needs, and the need for system innovations for achieving sustainable development (Jansen 2003; Quist 2002). This awareness also involves the potential contribution technology development can make to moving cities to sustainability, in addition to how technology has been developed and used so far and how this has contributed to solving the current sustainability problems (see Quist et al. 2006). This is of particular relevance to the aforementioned Ph.D. project in terms of using ICT of pervasive computing for advancing sustainable urban forms (see Bibri and Krogstie (2017b) for a conceptual framework).

11.9 Conclusions

The principle aim of this chapter was to review the existing backcasting methodologies and discuss the relevance of their use in terms of their steps and guiding questions in analyzing strategic smart sustainable city development as an area that is at the intersection of city development, sustainable development, and technology development, as well as to synthesize a backcasting approach based on the outcome of the review and discussion. This approach in turn is illustrated by the Gothenburg 2050 Project and an ongoing Ph.D. project as case studies. Smart sustainable cities are seen as the most important arena for sustainability transitions and thus of crucial importance for global futures, as they constitute key sites of environmental, economic, and social innovations making significant contributions to societal transformation and cultural advancement. However, there is no single or simple formula for achieving smart sustainable cities. Drastic changes of such kind require though long-term strategic planning, where futures studies can serve as a basis for inspiration in discussion and decision-making processes. The primary purpose of futures studies is to get a better understanding of future opportunities and to explore the implications of alternative development paths that can be relied on either to adapt or to avoid the impacts of the future. There is a belief that future-orientated planning can change development paths. The interest in smart sustainable city future is driven by a willingness and desire to transform the continued development path. Further, there are a number of different approaches to futures studies. Of these, backcasting is the most promising approach to developing action plans for achieving urban sustainability, more specifically smart sustainable cities. Using backcasting, futures studies are intended in this context to help people better understand future possibilities of models for smart sustainable city and their feasibility and potential in order to make better decisions today. They are also intended to challenge present systems or to influence the future or adapt to the most likely future. Creating a choice of the future by outlining a sustainable alternative forms the basis for strategic planning. Also, they are meant to aid people in examining and clarifying their normative scenarios of the future, transforming their visions, and then developing action plans. In view of that, they can be used to provide an analytical framework for policy decisions in the identification of opportunities for integrating the novel applications of advanced ICT with the design concepts and planning principles of sustainable urban forms in the context of smart sustainable cities of the future. The role of futures studies has become of central importance for policymaking process in the context of urban sustainability. Being normative, futures studies provide a useful framework for supporting policymakers and facilitating and guiding their actions to reach urban sustainability. Also, alternative futures based on backcasting are capable of generating new policy directions needed if cities are to become smart sustainable reveal the relative implications of policy targets, and determine new opportunities for policymaking. Furthermore, backcasting encourages the searching for new development paths when the conventional ones do not seem to solve the problem, or when the available solutions may create new problems. Accordingly, it is clear that backcasting as a scholarly and planning approach dominates in dealing with strategic planning and development in the context of urban sustainability, not least within technologically and ecologically advanced nations in Europe. Backcasting has been applied to different urban domains in the context of urban sustainability, including energy, mobility, transportation, land use, environment, waste management, and design. Thus, backcasting has been employed on a variety of topics related to different aspects of urban sustainability.

Beyond the scientific interest in applied city foresight in relation to sustainability, there are practical reasons for studying smart sustainable cities. The implication of increasing resource use is greater loss of natural assets and larger ecological footprints, with economic and societal implications. Urban policymakers should be encouraged to understand the past, present, and future conditions of their cities to determine the most strategic steps to achieve different forms of success pertaining to the long-term goals of sustainability in an increasingly technologized and computerized urban world. The analysis of the more recent studies that have applied the backcasting approach to develop plans for sustainability projects has underlined the effectiveness and efficacy of this approach in terms of indicating policy pathway for sustainability transitions and realizing sustainable systems. Thus, backcasting is a suitable and useful framework for supporting policymakers and facilitating and guiding their actions to instigate sustainable transformations. The choice of such framework to develop scenarios of smart sustainable cities is supported by its appropriateness to reach the policy targets (sustainable development goals) in tandem with societal development. The backcasts of different alternative futures are intended to reveal the relative implications of different policy targets, as well as to determine the opportunities for policymaking. Important to highlight is that the choice of including sustainability issues and backcasting visions in urban planning is more of a political challenge than a scientific one. The real challenge lies, arguably, in the acceptability of the sustainability targets and visions and the associated instruments and measures. Hence, it is important to elaborate the topic being analyzed and to approach the relevant stakeholders and experts on their topic. This is to shun confronting with the issue of public acceptance and the process of generating stakeholder support, commitment, and contribution. In light of this, the government is, through regulatory policies, the central regulating actor that should stimulate and force smart sustainable urban development. However, it is important to take into account the restrictions and difficulties that governments face with regard to sustainability transitions. Moreover, the government may be politically fragmented, and democratically elected governments are likely to slow down change processes (even within ecologically and technologically advanced nations) due to potential vested interests of strategic stakeholders with political power (e.g., Quist et al. 2006) This is likely to be attributed to the prevailing economic and political models and institutional structures pertaining to urban development. Related programs and initiatives involve making countless and integrated decisions about urban form, urban design, sustainable technologies, and governance (Bibri and Krogstie 2016). Smart sustainable cities as promising and desirable future alternatives face cultural and structural hurdles, and are usually more difficult to deal with, especially in advanced societies. Regardless, societal transitions with their long-term orientations and complex transformative processes are necessary for moving toward sustainability.

Furthermore, there are several approaches to backcasting. While they differ in their steps and thus guiding question, they do converge on the essentials. The backcasting framework is adaptive in nature within its steps and thus guiding questions based on the specific context under which it is applied, the stakeholders involved, and the complementary methods to be used. Therefore, it is common to adjust the backcasting framework for application in different research projects depending on the topic, purpose, scope, and complexity of futures studies to undertake, as well as on the time and resources available and the presence of dependencies between stakeholders and power issues among them. For example, taking into account all the dimensions of participatory backcasting in an integral approach in a rather limited timeframe might result in some tension between, on one hand, the adherence to the application of all the steps of the backcasting approach by soundly using the related guiding questions and, on the other hand, obtaining the results on the topic that make sufficient sense and derive from a deeper understanding of the approach and its range of dimensions (see Quist et al. 2006). Interestingly, different approaches are emerging in the field of urban sustainability within various city domains.

In light of the above, this chapter endeavored to synthesize a scholarly and planning approach based on the findings and insights drawn from the review and discussion of various backcasting approaches, and further illustrated it by the case study the Gothenburg 2050 Project. Below is the outline of the synthesized scholarly and planning approach to strategic smart sustainable city development:

- Defining normative assumptions and setting criteria and goals in relation to urban sustainability;
- Describing the current situation, prevailing trends, and expected developments;
- Constructing an image of the future for smart sustainable city;
- Backcasting analysis; and
- Elaboration and implementation.

The pioneering work of the Project Gothenburg 2050 is a Swedish exemplar case in the application of backcasting for strategic sustainable urban planning. It uses backcasting to develop action plans from a shared vision of the future. It is a research project in its nature. It tries to develop, compile, and disseminate knowledge of sustainable society. Hence, it seems theoretical in its overall approach. In it, the driving factor is to achieve the sustainable society that is defined by the project's stakeholders. The project engages with universities, research councils, the energy sector, local government, and citizens who are interested in the project. The concept of sustainability is clarified by stakeholders, which leads to a shared vision of the future sustainable city.

A way of approaching the definition of the future is to create a vision of that future, which describes in the context of the ongoing Ph.D. project how the city can develop to a smart sustainable one. This project consists in generating a sustainable future vision and turning it, through backcasting analysis, design activities, and impact analysis, into follow-up agendas, planning for actions, and realizing follow-up activities. Höjer and Mattson (2000) emphasize the importance of scrutinizing how to attain that future, identifying the necessary measures and actions for bringing about that future. In all, backcasting in the Ph.D. project is about generating a sustainable future vision, performing different analyses, and identifying what institutional, organizational, regulatory, urban, technological, and other changes are necessary to realize that vision. The focus of this backcasting project is on the key unexploited benefits, opportunities, capabilities, impacts, possible routes, and future scenarios enabled by ICT of pervasive computing for urban sustainability in terms of advancing sustainable urban forms in such a way to strategically improve and sustain their contribution to the goals of sustainable development.

In general, the backcasting approach is found to be well suited for long-term urban sustainability solutions, and indeed is the most widely recognized and applied approach to futures studies dealing with urban sustainability issues due to its normative, goal-oriented, and problem-solving character. Also, it is useful when: dealing with complex problems and transitions, the current trends are part of the problem, and different directions of development can be allowed given the wide scope and long time horizon considered. A number of recent futures studies using backcasting have underlined the efficacy of this scholarly and planning approach in terms of indicating policy pathway for sustainability transitions and thus supporting policymakers and facilitating and guiding their actions. The synthesized scholarly and planning approach serves to help researchers and scholars in analyzing strategic smart sustainable city development to assist planners, policymakers, and decision-makers in their endeavor to implement smart sustainable cities. In addition, it is meant to save the time and effort involved in reviewing, contextualizing, and adapting available methodological frameworks for backcasting to develop future models for smart sustainable city, a holistic urban development approach that will prevail for many years yet to come due to the global trends currently at play across the world: the diffusion of sustainability, the spread of urbanization, and the rise of ICT.

Lastly, backcasting is a very effective means for collective learning, especially in relation to the interdisciplinary nature of the approach, considering the social aspects of systems and technologies, the focus on fulfilling the goals of sustainable development and thus societal functions, the long-term orientation necessary for sustainability transitions, and the complexity of sustainability challenges and problems. The topic of smart sustainable city development is inherently interdisciplinary, adding to the fact that different urban stakeholders can have strongly different views and their stakes, interests, and values are at play. Therefore, the opportunities for learning are enormous.

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