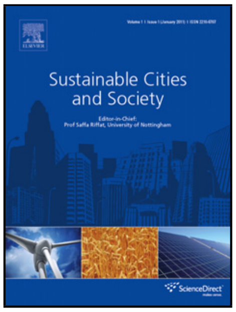

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ICT of the New Wave of Computing for Sustainable Urban Forms: Their Big Data and Context–Aware Augmented Typologies and Design Concepts

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Abstract

Undoubtedly, 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 that will enable built environments to function in a more constructive and efficient way. However, 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 evaluation and improvement of their contribution to the goals of sustainable development. 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 current and future ICT has to offer as innovative solutions and sophisticated methods so as to thrive—i.e. advance their contribution to sustainability. The need for ICT of the new wave of computing to be embedded in such forms is underpinned by the recognition that urban sustainability applications are deemed of high relevance to the contemporary research agenda of computing and ICT. To unlock and exploit the underlying potential, the field of sustainable urban planning is required to extend its boundaries and broaden its horizons beyond the ambit of the built form of cities to include technological innovation opportunities. This paper explores and substantiates the real potential of ICT of the new wave of computing to evaluate and improve the contribution of sustainable urban forms to the goals of sustainable development. This entails merging big data and context–aware technologies and their applications with the typologies and design concepts of sustainable urban forms to achieve multiple hitherto unrealized goals. In doing so, this paper identifies models of smart sustainable city and their technologies and applications and models of sustainable urban form and their design concepts and typologies. In addition, it addresses the question of how these technologies and applications can be amalgamated with these design concepts and typologies in ways that ultimately evaluate and improve the contribution of sustainable urban forms to the goals of sustainable development. The overall aim of this paper suits a mix of three methodologies: literature review, thematic analysis, and secondary (qualitative) data analysis to achieve different but related objectives. The study identifies four technologies and two classes of applications pertaining to models of smart sustainable city as well as three design concepts and four typologies related to models of sustainable urban form. Finally, this paper proposes a Matrix to help scholars and planners in understanding and analyzing how the contribution of sustainable urban forms to sustainability can be improved through ICT of the new wave of computing and its novel technologies and applications, as well as a data–centric approach into evaluating this contribution and a simulation method for strategically optimizing it.

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1. Introduction

In contemporary cities, urban systems—processes which operate and organize urban life in the form of built environment, infrastructure, ecosystem services, human services, and administration—are under increasing pressure due to the greatest wave of urbanization in history, coupled with the enormous challenge of sustainability of our time. This is primarily due to the form of contemporary cities, which has been seen as a source of sustainability problems (e.g. Alberti et al. 2003; Beatley and Manning 1997; Bibri and Krogstie 2017a; Hildebrand 1999; Jabareen 2006; Sev 2009). The current built environment 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 (Bibri and Krogstie 2017a). Therefore, the current built form affects people, natural resources, habitat, and climate (Jabareen 2006). These effects are set to worsen with the rapid urbanization of the world. 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; OECD 2012). This is because it puts an enormous strain on urban systems, i.e. stresses urban life in terms of the underlying operating and organizing processes, functions, and services, which stems from the ensuing intensive energy consumption, endemic congestion, saturated transport networks, air pollution, resource depletion, community expansion, social vulnerability, public health decrease, and so on (Bibri and Krogstie 2017a).

Undoubtedly, sustainability has, over the last two decades or so, been instrumental in transforming the core practices, primary operations, and central institutions of urban society in response to the goals of sustainable development. This has led to the emergence of several models of sustainable urban form as instances of sustainable cities, particularly in ecologically advanced nations. Contemporary debates in urban and academic circles continue to focus on the role of sustainability in urban planning and development in terms of responding to the continuous challenge pertaining to the unsustainability of existing urban forms as well as to the rapid urbanization of the world (Bibri and Krogstie 2017a). The way forward for cities to better cope with the changing and restructuring conditions is to adopt the long–term approaches that focus on sustainability (see Bulkeley and Betsill 2005). This is to mitigate the adverse effects that these cities might encounter as a result of stretching beyond the capacities and designs of urban systems accompanying urban growth (e.g. Antrop 2004).

In addition, ICT has become part of mainstream debate on urban sustainability as well as urbanization due to the increasing ubiquity presence of computing and the massive use of ICT in urban systems and domains. This is underpinned by the recognition that the planning of cities as dynamic and evolving systems towards sustainability in terms of how they function and can be managed and developed necessitates smart and data–centric technologies (e.g. Bibri and Krogstie 2016a). Besides, the way cities can intelligently be designed has been of fundamental importance for strategic sustainable development to achieve the long–term goals of sustainability (Bibri and Krogstie 2017a). The planning of cities as complex systems towards sustainability requires innovative solutions and sophisticated methods and techniques (e.g. Colldahl, Frey and Kelemen 2013; Kramers et al. 2014; Rotmans, van Asselt and Vellinga 2000; Shahrokni et al. 2015). ICT plays a key role in smart sustainable urban planning (Bifulco et al. 2016). Indeed, it has proven role in supporting sustainable cities in their contribution to the goals of sustainable development, particularly in relation to the operation, management, and planning of urban systems (e.g. Bibri and Krogstie 2017a, b). Besides, it is important to understand how smart solutions relate to and thus contribute to sustainability (Bifulco et al. 2016). In view of that, innovative solutions and sophisticated approaches are needed to overcome the current challenges and problems facing sustainable urban forms as instances of sustainable cities. This pertains to how such forms should be monitored, understood, analyzed, and planned to improve the contribution to the goals of sustainable development (Bibri and Krogstie 2017a). Regardless, we live in a world where ICT has become deeply embedded into the very fabric of contemporary cities, i.e. urban operations, functions, services, and designs are pervaded with computation and intelligence. It follows that for existing models of sustainable urban form to prosper, they need to embrace what ICT has to offer in order to smarten up as to making urban living more sustainable—in an increasingly computerized urban society. This is predicated on the assumption that emerging and future ICT offers tremendous potential for monitoring, understanding, probing, assessing, and planning sustainable cities, which can be leveraged in the improvement of urban sustainability on several scales (Bibri and Krogstie 2016a; 2017a). ICT is already enabling cities in many parts of the world to remain sustainable and thus livable in the face of many challenges.

In the event of the evolving ICT of the new wave of computing (Bibri and Krogstie 2016a), recent research has started to focus on incorporating sustainability in smart city approaches and on smartening up sustainable city models (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). This entails integrating the foundations of the established urban sustainability knowledge with the available technological solutions in an attempt to achieve the required level of sustainability with respect to urban operations, functions, services, and designs. This is increasingly seen as a holistic approach into urban planning and development, which holds great potential to address the challenge of urban sustainability (e.g. Bibri and Krogstie 2017a). Thereby, the concept and development of smart sustainable cities are rapidly gaining momentum as an epitome of this holistic approach and as an academic pursuit in ecologically and technologically advanced societies (Bibri and Krogstie 2016a). It is worth noting that the emergence of these new techno–urban phenomena has been fueled the new digital transition, manifested in what is labeled ‘ICT of the new wave of computing’—i.e. a combination of various forms of pervasive computing, of which the most prevalent are Ubiquitous Computing (UbiComp), Ambient Intelligence (AmI), the Internet of Things (IoT), and Sentient Computing (SenComp) (Bibri and Krogstie 2016a)—and its integrative and constitutive nature, coupled with its advanced big data and context–aware applications. Major cities across the globe are increasingly engaging on this technological transition (see, e.g., Batty 2012; Bibri and Krogstie 2016a; Al Nuaimi et al. 2015; Solanas et al. 2014). The underlying assumption is that this transition is projected to bring about further transformational urban effects resulting from capturing further and invigorating the application demand for the urban sustainability solutions that future ICT can offer. The convergence of future ICT will shape future cities in fundamental—and yet unexperienced—ways (see, e.g., Batty et al. 2012; Shepard 2011). It has been suggested that as ICT becomes spatially all pervasive, located anywhere and everywhere across urban environments, i.e., data sensing, information processing, and wireless communication networking become more and more combined with infrastructure, architecture, ecosystem services, human services, and even citizens’ bodies, 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 (e.g. Batty et al. 2012; Bibri and Krogstie 2016a, 2017a; Böhlen and Frei 2009; Piro et al. 2014; Shepard 2011; Townsend 2013).

With the above in mind, sustainable urban forms as complex systems, with their domains becoming subtly interconnected and their processes highly dynamic, rely more and more on sophisticated technologies to realize their full potential for responding to the challenge of sustainability (Bibri and Krogstie 2017a, b). The most influential of such technologies are big data analytics and context–aware computing,which are enabled by ICT of the new wave of computing. Worth pointing out is that in the near future, the core enabling technologies of ICT of the new wave of computing, namely digital sensing devices, data processing platforms, cloud computing infrastructures, middleware architectures, and wireless communication networks, will be the dominant mode of monitoring, understanding, analyzing, evaluating, and planning sustainable urban forms as sustainable cities to improve their contribution to the goals of sustainable development. Big and context data constitute the fundamental ingredients for the next wave of urban analytics and computing (Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Solanas et al. 2014; Zheng et al. 2014a), irrespective of whether cities are sustainable, smarter, or smart sustainable. Indeed, contemporary cities need to be dynamic in their conception, scalable in their design, efficient in their operational functioning, flexible in their planning, and effective in their evaluation in order to be able to deal with population growth, environmental pressures, socio–economic need changes, unpredictable dynamics, and new trends. In a recent interdisciplinary literature survey, Bibri and Krogstie (2017a) report that ‘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. This pertains to limitations, uncertainties, paradoxes, and fallacies… The underlying argument is that urban systems have been in themselves complex in terms of their operation, management, assessment, and planning in line with the vision of sustainability.' Of most relevance of the issues and debates addressed in their work as to this paper is that the issue of sustainable urban forms has been problematic and difficult to deal with, particularly when it comes to the evaluation and improvement of the contribution of such forms to the goals of sustainable development.

The original contribution we make with this study is to explore and substantiate the real potential of ICT of the new wave of computing to evaluate and improve the contribution of sustainable urban forms to the goals of sustainable development. This entails merging big data and context–aware technologies and applications with the typologies and design concepts of sustainable urban forms to achieve multiple hitherto unrealized goals. In doing so, this paper seeks to answer the following questions: What are the distinctive smart sustainable cities and sustainable urban forms proposed by urban development approaches and strategies? And what are the technologies and applications and the design concepts and typologies that these cities and forms share, respectively? In addition, the paper aims to offer a conceptual framework for merging these technologies and applications with these design concepts and typologies, as well as to propose a data–centric approach and simulation method into evaluating and strategically optimizing the contribution of sustainable urban forms to the goals of sustainable development, respectively. The main motivation for this paper is to put forward novel solutions for effectively translating sustainability into the built environment of sustainable urban forms, as well as to suggest advanced methods for evaluating the extent to which such forms contribute to the goals of sustainable development and how this contribution can strategically be enhanced over the long run.

The remainder of this paper consists of 9 sections. Section 2 focuses on the methodologies of the study. The study adopts, and thus combines, literature review, thematic analysis, and secondary data analysis. In Section 3, we introduce, describe, and discuss the relevant conceptual and theoretical constructs that make up the study. In section 4, we provide an overview of the field of sustainable urban forms in terms of its state–of–the art research and development, knowledge gaps, and technological opportunities. Section 5 presents the operational aspects (design concepts and typologies) of models of sustainable urban form and the operational facets (technologies and applications) of models of smart sustainable city to examine them more accurately, as well as discusses the specific urban forms and cities associated with sustainability that appear in the literature. In section 6, we describe and discuss the integration of the technologies and applications of models of smart sustainable city with the typologies and design concepts of models of sustainable urban form to improve the contribution of the latter to the goals of sustainable development. We moreover offer a conceptual framework for illustrating this integration. Accordingly, a Matrix is proposed to help academic researchers and urban planners in understanding and analyzing how the contribution of sustainable urban forms to sustainability can be improved through ICT of the new wave of computing. Section 7 justifies the need for a data–driven approach into evaluating the contribution of sustainable urban forms to sustainability from an environmental and socio–economic perspective, and elucidates how this evaluation can be done. It also proposes simulation models as a suitable method for strategically enhancing this contribution. This section highlights the effectiveness and appropriateness of urban ICT as to carrying out such complex urban tasks in the realm of sustainable urban forms. Section 8 identifies and discusses the various challenges pertaining to ICT of the new wave of computing as well as big data analytics and context–aware computing technologies. The final section draws some conclusions, provides contributions and reflections, and suggests several issues for future research.

2. Methodologies

The intent of this paper suits a mix of three approaches: (1) literature review, (2) thematic analysis, and (3) secondary data analysis to achieve different but related objectives. The first approach provides an overview of the area of sustainable urban forms in terms of its state–of–the art research and development, knowledge gaps, and technological opportunities. Specifically, the paper reviews existing models of sustainable urban form, discusses their weaknesses, and identifies related challenges with particular emphasis being placed on the extent to which such forms contribute to the goals of sustainable development. The relevant research gaps and technological opportunities are highlighted in accordance with the topic being explored.

As to the second approach, it is assumed that in existing models of sustainable urban form (Jabareen 2006) and recent models of smart sustainable city (Bibri and Krogstie 2017a), there are concepts and technologies that repeat themselves and compose distinct models of sustainable urban form as well as smart sustainable city, respectively. Therefore, the paper uses a qualitative approach to identify these models and their design concepts and typologies as well as their technologies and applications, and, eventually, to identify the urban concepts and technological constructs behind them. The purpose is to figure out at what levels these two classes of models can be integrated to advance urban sustainability. 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 planning and design 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. First, to identify the most sustainable models of sustainable urban form and their design concepts and typologies. Second, to identify the most sustainable models of smart sustainable city and their technologies and applications. And subsequently to conceptualize the theoretical base behind these two classes of models along with the underlying 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 the large qualitative data that include 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 (e.g. case studies). It can be applied to produce theory–driven analyses.

The main steps of this study'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. The outcomes of this process are various design concepts, typologies, technologies, applications, and themes that are related to these two classes of models.
2. Pattern recognition entails the ability to discover meaningful patterns and relationships in seemingly random information (e.g. Boyatzis 1998), 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 (typologies, design concepts, technologies, and applications).
3. Identifying urban forms and cities involves recognizing specific and distinctive urban forms and cities associated with sustainability.
4. Conceptualization is about finding theoretical relationships among the identified concepts and urban forms and cities.

Our third approach is an example of what is called 'secondary data analysis' since we deal with secondhand data. Secondary data denote that the data are collected by someone other than the researcher(s). Its relevance lies in that the analyst of urban transformation (e.g. smart sustainable urban forms) considers these data essential, a long as they can adequately capture recent urban transformation. Further, to overcome some of the shortcomings associated with secondary data, we ensure the data used are up–to–date and pertain to research focusing on ICT of the new wave of computing for urban sustainability in relation to big data analytics and context–aware computing. However, there are very few relevant high–quality documents available for reanalysis. Worth noting is that secondary data analysis herein is concerned with the reuse of qualitative data, and this provides an opportunity to study the material of the very recent past concerning smart sustainable urban planning and development to gain insights for theoretical purposes. In addition, the aim of the secondary analysis of qualitative data is not only to analyze pre–existing qualitative data, but also to re–contextualize and re–construct these data with respect to smart sustainable urban forms as an emerging city planning and development strategy.

3. Conceptual and Theoretical Background

3.1. 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 Beatley 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.), to draw on Bibri (2013). 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 iterate, 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 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 decision–making and planning in the realm of sustainable cities (Bibri and Krogstie 2017), not to mention smart cities due to the multidimensional risks they pose to environmental sustainability (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). Even though these goals co–exist 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 paper, the focus is on the smart dimension of urban sustainability and sustainable urban development. In this regard, smart 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 urban computing and ICT—to achieve the sought after smart form of urban sustainability. This can occur through the process of change and strategic approach of sustainable urban development that—in seeking to foster and promote sustainable urban forms, environmental integration, economic development, and social equity as interrelated goals—relies on smart ICT in terms of innovative solutions and novel approaches by unlocking the untapped potential for sustainable transformation that ICT embodies in its morphing and disruptive power as an enabling, integrative, and constitutive technology. The respective change process and strategic approach ought to be driven by linking the research agenda of urban computing innovation and urban ICT development with the agenda of sustainable urban development, thereby justifying ICT investment and its orientation by environmental concerns and socio–economic needs in this context. This endeavor should be supported by pertinent institutional structures and practices.

3.2. 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, Burton and Williams 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 paper, 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. For detailed definitions of sustainable urban development and urban sustainability, the reader can be directed to Bibri and Krogstie (2017a).

Sustainable development has significantly impacted the development of city models in terms of different dimensions of sustainability (e.g. Jabareen 2006; Hofstad 2012; Joss 2011; Girardet 2008; Williams, Burton and Jenks 2000). Unquestionably, it has inspired and motivated a generation of urban scholars and practitioners into a quest for the immense opportunities enabled and 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 wellbeing.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). 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**,** Burton and Jenks 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). A sustainable urban form can be conceived of as an urban form for human settlements that seeks to meet the required level of sustainability by enabling the urban systems (built form, infrastructure, ecosystem services, human services, and administration) and thus the urban domains to function in a constructive way (Bibri and Krogstie 2017). Using a thematic analysis approach, Jabareen (2006) classifies sustainable urban forms into four models entailing overlaps in their concepts, ideas, and visions: (1) compact city, (2) eco–city, (3) neotraditional development (new urbanism), and (4) urban containment. This paper is concerned with the first three urban forms in terms of integrating the underlying typologies and design concepts as well as environmental and urban management systems 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).

3.3. ICT of the New Wave of Computing: The Dominant ICT Visions

3.3.1. Short on Urban Computing and ICT

The theoretical and disciplinary orientation of computing and ICT differentiate their meaning as concepts, although they often are used interchangeably. Hence, it is worth pointing out the main difference to give perspective. ICT theory is concerned with the application of ICT 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). For a detailed definition of urban computing and ICT, the reader can be directed to Bibri and Krogstie (2017a). 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 share 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 improve urban operational functioning, advance urban planning, enhance the quality of life of citizens, facilitate urban daily activities, understand the nature of urban phenomena, and predict urban shifts. The new wave of computing is associated with the amalgamation of the most prevalent visions of ICT: UbiComp, AmI, the IoT, and SenComp.

3.3.2. 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 21st 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, to draw on Bibri (2015b). 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 (2015b) for a comprehensive 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 (e.g. Bibri 2015a), 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, Harrison and Michahelles 2011) refers to a computationally augmented everyday environment where the physical world (everyday objects) and the information world (information processing) 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 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 (Bibri 2015b).

3.3.3. Emerging Smart Sustainable and Smarter Cities as Instances of ICT of the New Wave of Computing for Urban Sustainability

The rationale behind selecting and thus defining the above concepts 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 (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 an Internet of everything (e.g. Kyriazis et al. 2014). Worth mentioning is that these cities are considered as future visions of smart cities. 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 healthcare, 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. Further, these cities are labelled 'smarter cities' because of the magnitude of ICT and the extensiveness of data as to their embeddedness and use respectively 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 computing infrastructures, data processing platforms, middleware architectures, and wireless communication networks across various spatial scales.

Smart sustainable cities typically rely on the fulfillment of ICT visions of the new wave of computing (Bibri and Krogstie 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 the prevalent 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). As regards to the conceptual categories of models of smart sustainable city (and sustainable urban form), they are an integral part of the thematic analysis covered in Section 5.

3.4. 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, which renders the processing of these 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 traditional data processing systems. Traditional analytic systems are not suitable for handling big data (e.g. Katal, Wazid and Goudar 2013; Khan, Uddin and Gupta 2014). This implies that big data entails the use of tools (e.g. classification, clustering, and regression algorithms), techniques (e.g. data mining, machine learning, and statistical analysis), and technologies (e.g. Hadoop, HBase, and MongoDB) that work beyond the limits of the data analytics approaches that are used to extract useful knowledge from large masses of data for timely and accurate decision–making and enhanced insights. The European Commission (2012) defines big data as ‘high–volume, high–velocity and high–variety information assets that demand cost–effective, innovative forms of information processing for enhanced insight and decision–making.’ 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 big urban data based on existing computing 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.

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. Laney 2001; Fan and Bifet 2013). Additional Vs include veracity, validity, value, and volatility (e.g. Khan, Uddin and Gupta 2014). The emphasis here is on the main characteristics of big data, namely the huge amount of data, the wide variety of data types, and the velocity at which the data can be analyzed.

- 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).

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, 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, policies, and practices). 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 pertaining to various urban domains, such as transport, mobility, traffic, environment, energy, land use, planning, design, safety, healthcare, and education. Further, 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 then 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 remains the most widely used technique in the urban domain, and presents a tremendous challenge due to the interdisciplinary and multidisciplinary nature of urban data. It refers to the automated extraction of useful knowledge from large datasets, which 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.

Data processing platforms are a key component for the design, development, and implementation 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 technologies for big data storage and processing 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 technologies usually entail scalable, evolvable, optimizable, and reliable software and hardware components, and provide high performance computational capabilities (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 data analytics related to a wide variety of large–scale applications intended for different uses, such as management, control, optimization, assessment, and improvement, thereby spanning a variety of urban domains and subdomains. In more detail, the resulting knowledge can be used for making, supporting, or automating decisions, which entails control, optimization, management, and planning of urban operations and processes, enhancement of ecosystem and human services, and improvement of urban practices and policies. (See Bibri and Krogstie 2017b for a detailed overview). Thereby, the analytical outcomes of urban data can serve to improve urban operational functioning, optimize resources, reduce urban environmental risks, and enhance the quality of life and well–being of citizens. Big data as a research direction has recently attracted scholars and scientists from diverse disciplines as well as practitioners from a variety of professional fields due to its prominence in relation to various urban domains, especially mobility, transportation engineering, planning, public health, education, socio–economic forecasting, environment, and energy, 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; Khan et al. 2015).

3.4. Context–Aware Computing

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, Beigl and Gellersen 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' (Bibri 2015a, p. 1) by enabling sensorily and computationally augmented environments to provide the most efficient services pertaining to healthcare, education, learning, safety, utility, housing, and so on. In recent years, 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; Böhlen and Frei 2009; ISTAG 2003, 2008, 2012; Solanas et al. 2014). In this context, context–aware computing aims to provide control over processes and support decision-making (Bibri 2015a), where 'adaptation are based either on pre-programmed heuristics or real-time reasoning capabilities' (Oulasvirta and Salovarra 2004). The purposes of machine learning and reasoning are monitoring the actions of systems and the changes in their environment using sensors of many types as well as physical actuators to react and pre-act in relevance to optimization, management, and control of urban operations. 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 and systems can monitor what is happening in urban environments (situations, events, states, 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 mobility, smart healthcare, or smart safety—across several spatial scales. Here the context denotes, drawing on Chen and Kotz (2000), the environmental states and settings within the urban landscape that either determine applications' behavior or in which application events occur and are interesting to the citizens or urban actors (e.g. city administrators, authorities, and departments) as users.

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 (e.g. traffic system, energy system, healthcare system, education system, information system, human user, 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). 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 applications and systems in the urban domain 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).

4. State–of–the–Art Overview

Scholars from different disciplines and practitioners from different professional fields have, over the past two decades or so, sought a variety of models of sustainable urban form that can contribute to sustainability and its improvement. Compact city, eco–city, and new urbanism (e.g. Bohl 2000; Jenks, Burton and Williams 1996a, b; Joss 2010, 2011; Joss, Cowley and Tomozeiu 2013; Leccese and McCormick 2000; Neuman 2005; Pendall, Martin and Fulton 2004; Register 2002) are the most prevalent and sustainable models of sustainable urban form (e.g. Jabareen 2006; Kärrholm 2011; Hofstad 2012; Rapoport and Verney 2011). Sustainable urban forms 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 advanced environmental and urban management systems (e.g. Jabareen 2006). However, the challenge continues to motivate and induce academics and planners 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 environmental, economic, social, and cultural dimensions (Bibri and Krogstie 2017a). The ultimate goal revolves around developing more convincing and robust models of sustainable urban form, which has been one of the most significant intellectual challenges and research endeavors for more than two decades (Bibri and Krogstie 2017a). As concluded by Jabareen (2006, p. 48), ‘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.’ One implication of this is that it has been difficult to evaluate whether and the extent to which the so–called sustainable urban forms contribute to the goals of sustainable development, as well as to translate sustainability into the built environment of sustainable cities, as well as to maintain sustainability improvement (Bibri and Krogstie 2017a; Jabareen 2006; Neuman 2005; Kärrholm 2011).

Whether in discourse, theory, or practice, the issue of sustainable urban forms 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 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 (e.g. Jabareen 2006; Hildebrand 1999a) and anthologies (Williams, Burton and Jenks 2000; Jenks and Dempsey 2005) a consensus on topics of relevance to urban 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 (see, e.g., Harvey 2011; Tomita et al. 2003; Williams, Burton and Jenks 2000). Regardless, 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). As to compact city, for instance, Williams, Burton and Jenks (1996) argue that the actual effects of many of the claimed benefits of the compact city are far from certain. As supported by Newman (2005), evidence testing the compact city vis–à–vis sustainability suggests that the relation between compactness and sustainability can be negatively correlated, weakly related, or correlated in limited ways. Also, the correlation between mixed–land use and car travel is difficult either to confirm or to interpret (Rutherford, McCormack and Wilkinson 1996). Additionally, empirical studies by Breheny (1992) and Williams, Burton and Jenks (2000) are not conclusive about the link between higher densities and reduced automobile trips. Growth in car ownership and business travel, as well as increasingly dispersed life patterns, have led to the inability of physical design alone to reduce travel demands of energy–rich transport modes (Williams, Burton and Jenks 2000). In all, as argued by Neuman (2005), advocates of compact city remain on the same playing field with their counterparts in terms of the performance as to achieving sustainability goals, and they have not raised the level of the game; rather, they have reverted back to an old game.

The above arguments also clearly point to the difficulty and uncertainty surrounding the translation of sustainability into the built form and thus its improvement. In this regard, Neuman (2005) contends that conceiving cities in terms of forms remains inadequate to achieve the goals ascribed to the compact city; 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 relation to this, 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). For similar critical views concerning the eco–city and new urbanism, the reader is directed to Bibri and Krogstie (2017a) and Neuman (2005), respectively.

However, the arguments discussed above provide valid reasons to believe that their conclusions are in accordance with the facts that it is timely and necessary to develop and apply innovative solutions and sophisticated approaches to deal with the challenge of sustainability in the context of sustainable urban forms. This would entail a blend of sciences, which ICT of the new wave of computing is extremely well placed to initiate in terms of addressing the complex issues related to sustainable urban forms given its foundation on the application of complexity and data sciences to urban systems and problems (see, e.g. Batty et al. 2012; Bibri and Krogstie 2016a, 2017a). A way forward for smartening up sustainable urban forms is to adopt the cutting–edge solutions being offered by recent models of smart sustainable city in terms of the underlying core enabling technologies and their novel big data and context–aware applications for sustainability (Bibri and Krogstie 2016a, 2017a). Indeed, in light of the recent smart and sustainable city development (e.g Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017a, b; Kramers et al. 2014; Solanas et al. 2014), ICT solutions have been leveraged in the advancement of many aspects of urban sustainability. Smart solutions involve ‘constellations of instruments encompassing sensing technologies, big data analytics, context–aware computing, cloud computing, and wireless communication networks and their use within diverse urban domains (e.g. transport, mobility, energy, environment, planning, healthcare, education, and safety).’ (Bibri and Krogstie 2017a, p. 23).

More specifically, it has become highly relevant and important in an increasingly technologized and computerized urban society to amalgamate the design concepts and typologies of sustainable urban forms with smart methods for the purpose of substantiating their practicality with regard to their contribution to sustainability, as well as to integrate them with smart solutions for the purpose of increasing their contribution to sustainability, in addition to evaluating to what extent they contribute to sustainability and identifying their untapped potential for achieving sustainability (Bibri and Krogstie 2017a). Important to note is that for many contemporary urban scholars, theorists, and planners, the design concepts and typologies of sustainable urban forms (compact city, eco–city, and new urbanism) are necessary to be adopted and implemented to achieve sustainability (e.g. Audirac and Shermyen 1994; Dumreicher, Jabareen 2006; Joss 2011; Levine and Yanarella 2000; Leccese and McCormick 2000; Rapoport and Verney 2011; Williams**,** Burton and Jenks 2000)—irrespective of how smartly the underlying urban systems and domains can be operated, managed, planned, and developed. Yet the role of ICT as an enabling and constitutive technology lies in the substantial contribution it can make to not only catalyzing and boosting the development processes of sustainable urban forms, but also monitoring, understanding, probing, assessing, and planning such forms to strategically improve their contribution to sustainability (Bibri and Krogstie 2017a, b).

The relevant gaps (see Table 1) in the research according to a recent literature review conducted by Bibri and Krogstie (2017a) in relevance to this paper include the following:

Relevant Research Gaps Pertaining to Sustainable Urban Forms
• There is no framework for merging the informational and physical landscapes of smart sustainable urban forms. • There is a need for approaches into applying smart ICT as a constitutive technology to further enhance the contribution of the typologies and design concepts of sustainable urban forms to sustainability. • There is need for combining the typologies and design concepts of sustainable urban forms with smart methods to evaluate their practicality with regard to their contribution to sustainability. • Sustainable urban forms remain inadequately scalable in design and flexible in planning without support of smart solutions and sophisticated approaches in response to urban changes. • There is a lack of conception of sustainable urban forms in terms of processual outcomes of urbanization, which is inextricably linked to smart ICT. • Sustainable urban forms fall short in considering several urban domains where smart solutions can

Relevant Research Gaps Pertaining to Sustainable Urban Forms
have substantial contributions in relation to sustainability.

Table 1. Relevant research gaps pertaining to sustainable urban forms

Table 2 highlights the relevant benefits of ICT for advancing the contribution of sustainable urban forms to sustainability, according to Bibri and Krogstie (2017a)

Relevant ICT benefits for Sustainable Urban Forms
• Smart 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 and substantiating the practicality of these typologies and design concepts as to their contribution to these goals. • Advanced tools and methods for realizing a dynamic conception of models of sustainable urban form in terms of processual outcomes of urbanization. • Smart applications for integrating and enhancing urban systems and facilitating collaboration 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, analysis, management, control, and optimization. • New ways of understanding and addressing urban problems and challenges.

Table 2. Relevant ICT benefits for sustainable urban forms

5. Design Concepts and Typologies of Sustainable Urban Forms and Technologies and Applications of Smart Sustainable Cities

The thematic analysis has identified three design concepts and four typologies along with significant themes related to different aspects of sustainability in the context of sustainable urban forms. It has moreover identified four technologies and two classes of their applications along with significant themes pertaining to different dimensions of sustainability in the context of smart sustainable cities. A number of themes are evident in current debates on both design concepts and typologies as well as technologies and their applications as important strategies and approaches for achieving desirable sustainable urban forms and smart sustainable cities, respectively.

5.1. Typologies and Design Concepts of Models of Sustainable Urban Form and Related Themes

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, Levine and Yanarella 2000; Jabareen 2006; Williams**,** Burton and Jenks 2000).

5.1.1. 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 CO2 emissions, and protecting rural land (e.g. Elkin, McLaren and Hillman 1991; McLaren 1992; Pratt and Larkham 1996; Williams, Burton and Jenks 2000).

5.1.2. Density

As a critical typology of sustainable urban forms, density denotes the ratio of dwelling units or buildings and their inhabitants to land area. 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. Walker and Rees 1997; Newman and Kenworthy 1989; Jabareen 2006). 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).

5.1.3. 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. 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, McLaren, and Hillman 1991; Ewing, Haliyur, and Page 1994; Jabareen 2006; Thorne and Filmer–Sankey 2003; Newman 1997; Parker 1994; Uyen–Phan and Senior 2000; Van and Senior 2000).

5.1.4. 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 socio–cultural 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 grey 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 diverse building types and land uses are today key for vibrant, attractive, and popular neighborhoods and districts, and concluded that zoning has diminished the diversity of urban form. For a sustainable urban form, zoning should be discouraged (see Breheny 1992b).

5.1.5. Sustainable Transport

It has been argued that transport is the major issue for environmental debates relating to urban form (Jenks, Burton and Williams 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, McLaren and Hillman (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 CO2 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, McLaren, and Hillman 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).

5.1.6. 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, Dunnett and Woolley 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, Levine and Yanarella 2000) by bringing nature into the life of citizens through diverse open landscapes (Elkin, McLaren and Hillman 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, Delshammar and Schildwacht 2003; Gilbert 1991; Jabareen 2006; Niemela 1999; Stulpnagel, Horbert and Sukopp 1990; Ulrich 1999; Von 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).

5.1.7. 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). How energy systems and urban structures interact occurs 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.

5.2. Models of Sustainable Urban Form

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) conceptually ranks the compact city as the most sustainable, followed by the eco–city, and then the new urbanism, with overlaps among them in their concepts, ideas, and visions as well as with some key differences and characteristic constructs. 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.

5.2.1. 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 1992b). Essentially, the compact city is a high–density, mixed–use city, and without sprawl (Jenks, Burton and Williams 1996a; Williams, Burton and Jenks 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 to 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 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 to hence promote efficient modes of transport (Sev 2009). In addition, population densities are adequate as to supporting local services and businesses (Williams, Burton and Jenks 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 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

Table 3. Compact city characteristics
Source: Neuman (2005)

5.2.2. 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, 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, 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, 64). This argument sides with Neuman's (2005) view regarding the static conception of urban forms and its disadvantages. Indeed, Durack (2011) 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.

5.2.3. 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 (2012) 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 socio–economic 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. Jabareen 2006; Council of Europe 1993; European Commission 1994; Robinson and Tinker 1998).

5.3. Technologies and Applications of Models of Smart Sustainable City

To achieve smart sustainable cities entails a combination of ICT of various forms of pervasive computing, i.e. UbiComp, AmI, the IoT, and SenComp technologies and their big data and context–aware applications (Bibri and Krogstie 2016a, b, 2017a).

5.3.1. UbiComp, AmI, the IoT, and SenComp: Differences, Commonalities, and Overlaps

The four identified technologies of models of smart sustainable city have already been described in Section 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. Bibri 2015a; 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 (e.g. Bibri 2015a). 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. Bibri 2015a; Bravo, Alaman and Riesgo 2006; Kyriazis et al. 2014; Shepard 2011). Lee et al. (2008) provides 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 (e.g. Bibri 2015a; Bibri and Krogstie 2017b). These technologies, tools, and techniques are in the context of this paper 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.

5.3.2. Demarcation Lines Between Applications of ICT of the New Wave of Computing

In the context of sustainable urban forms, the demarcation lines between Ubicomp, AmI, the IoT, and SenComp as computing fields and novel technologies concern in large part the kinds of applications they offer in relation to the domain of urban sustainability, rather than the underlying core enabling technologies and related computational and analytical processes and mechanisms. Specifically, the distinctions include the way in which the associated applications are used in connection with the diverse urban domains in relevance to the different strategies (typologies and design concepts) through which sustainable urban forms can be achieved. This implies that combining these varied applications is intended to provide significant opportunities to transform sustainable urban forms in terms of the processes that operate and organize urban life as to the built environment, infrastructure, administration, ecosystem services, and human services—urban systems—to achieve the goals of sustainable development. Efforts emanating from diverse computing fields 'modulate urban life and their effects overlap and reinforce one another' (Böhlen and Frei 2009, p. 1). Hence, the idea of coupling, integrating, and coordinating UbiComp, AmI, the IoT, and SenComp technologies and their novel applications is invaluable as to improving the contribution of sustainable urban forms to sustainability as to environmental, economic, and social dimensions. In all, with its varied, overlapping, and complementary applications, ICT of the new wave of computing is projected to add a whole new dimension to urban sustainability with regard to rendering the environmental, physical, human, and engineered systems of sustainable urban forms evolve in a manner that is more coordinated, efficient, and evolutional. The latter entails the gradual process in which existing models of sustainable urban form change into more complex and improved forms.

5.3.3. Applications of ICT of the New Wave of Computing

Significant opportunities exist for ICT of the new wave of computing—and hence big data analytics and context–aware computing—in relation to transforming the sustainable urban model. This is because the range of urban application areas that utilize UbiComp, AmI, the IoT, and SenComp in connection with sustainability is potentially huge, as these technologies usher in (big data) analytics and (context–aware) computing in nearly all urban domains. Common urban application areas include healthcare and social support, learning and education, public safety and civil security, energy efficiency and management, environmental monitoring and protection, transport efficiency and management, water and waste management, mobility and accessibility, urban infrastructure monitoring and management, medical and health systems, natural ecosystems, traffic management and street light control, strategic planning and efficient design (Bibri and Krogstie 2017a). For a list of original references for these application areas, the interested reader can look into a study conducted by Bibri and Krogstie (2016a) for details. In all, there is a lot to achieve with the deployment and implementation of ICT of the new wave of computing—as long as ICT development and innovation is linked to the agenda of sustainable development and investments in ICT are justified by the pursuit of overcoming the challenge of sustainability in terms of exploiting the benefits and capabilities of big data analytics and context–aware computing mainly to advance models of smart sustainable city.

However, recent studies (e.g. Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a, 2017a; Böhlen and Frei 2009; Lee et al. 2008; Shepard 2011; Shin 2009; Kyriazis et al. 2014) show that most of the applications pertaining to ICT of various forms of pervasive computing, which are based in relation to models of smart sustainable city on the notion of an amalgam of infrastructures and services to be directed towards 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 enabled and boosted by the recent advancements in several scientific and technological areas within computing, notably context awareness, multi–sensor data fusion, hybrid modeling and reasoning, machine learning, data mining, cloud computing, middleware architecture, wireless and mobile networks, and, more recently, big data analytics (Bibri and Krogstie 2016a).

5.3.4. Key Applications of Big Data Analytics and Context–Aware Computing

The two identified classes of applications of ICT of the new wave of computing pertain to big data analytics and context–aware computing. The conceptual categories have been defined and discussed in Section 3. The main strength of big data lies in the high influence it will have on many facets of models of smart sustainable city (e.g. Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a, b, 2017a, b; Khan et al. 2015; Pantelis and Aija 2013). Context–aware computing constitutes a key component of the infrastructures of models of smart sustainable city (e.g. Bibri and Krogstie 2016b, 2017a; Kamberov 2015; Solanas et al. 2014) and future cities (e.g. Riva et al. 2008). 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). Hence, there are many opportunities to embrace for models of smart sustainable city thanks to the use of big data and context–aware applications as to the role they will play in several important urban domains (e.g. Batty et al. 2012; Bibri and Krogstie 2016b, 2017a; Böhlen and Frei 2009; Shepard 2011; Solanas et al. 2014). 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 urban life in this direction by employing and merging data–centric and smart applications to enhance, harness, and integrate urban systems as well as facilitate collaboration and coupling among diverse urban domains.' 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 the following:

- Smart and data–centric 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);
- Smart and data–centric traffic lights and signals (e.g. Al Nuaimi et al. 2015; ISTAG 2003);
- Smart and data–centric energy (e.g. Al Nuaimi et al. 2015; Batty et al. 2012; Ersue et al. 2014; ISTAG 2003; Parello et al. 2014);
- Smart and data–centric 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);
- Smart and data–centric environment (e.g. ISTAG 2003; Li et al. 2011; Zheng, Liu and Hsieh 2013);
- Smart and data–centric buildings (e.g. Bibri and Krogstie 2016a, b; ISTAG 2008);
- Smart and data–centric public safety and civil security (ISTAG 2003; Shepard 2011);
- Smart and data–centric planning and design (e.g. Batty et al. 2012; Bibri and Krogstie 2016a; Nielsen 2011; Shahrokni et al. 2015);
- Smart and data–centric healthcare (Bibri 2015b; Solanas et al. 2014; Vongsingthong and Smanchat 2014; Zheng et al. 2014b; Zheng, Liu and Hsun–Ping 2013); and
- Smart and data–centric education (e.g. Al Nuaimi et al. 2015; Bibri and Krogstie 2016a; ISTAG 2003; Lee et al. 2008).
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Important to note is that smartness in this context is directed for the improvement of sustainability. As noted by Bibri and Krogstie (2017a, p. 34) in the context of sustainable urban forms, '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 sustainable 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.'

5.3.5. The Link between UbiComp, AmI, the IoT, and SenComp and Big Data Analytics and Context–Aware Computing

Big data trends are mainly associated with the IoT technology (e.g. Bibri and Krogstie 2017a; Batty et al. 2012; Vongsingthong and Smanchat 2014) and context data trends with 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 these trends as well as technologies. Of importance to underscore is that 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 (e.g. Bibri and Krogstie 2016a). Indeed, UbiComp and the IoT tend 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. Moreover, UbiComp and the IoT involve complex sensor infrastructures and networks for the objects involved are numerous and boundless (Bibri and Krogstie 2017a). However, in the near future, the core enabling technologies of these disruptive technologies, which involve big data analytics and context–aware computing and what these entail in terms of digital sensing technologies, cloud computing infrastructures, middleware architectures, and wireless communication networks, will be the dominant mode of monitoring, understanding, analyzing, assessing, operating, organizing, and planning smart sustainable and smarter cities to improve their contribution to the goals of sustainable development.

5.4. Models of Smart Sustainable City

Models of smart sustainable city represent the defining context of ICT of the new wave of computing for urban sustainability as a techno–urban discourse (Bibri and Krogstie 2016a). The main technologies and applications identified in relation to these models are associated with the goals of sustainable development. The urban domains concerned in this regard include transport, traffic, mobility, accessibility, energy, environment, economy, governance, life quality, equity, participation, healthcare, education, safety, planning, and design (Bibri and Krogstie 2017b).

5.4.1. Smart Sustainable Cities

Smart sustainable cities as a new techno–urban phenomenon have emerged around the mid–2010s (e.g. Al−Nasrawi, Adams and El−Zaart 2015; Bibri and Krogstie 2016a, b; Höjer and Wangel 2015; Kramers, Wangel and Höjer 2016; Rivera, Ericsson and Wangel 2015) as a result of several intertwined global shifts involving urbanization, sustainable development, sustainability, sustainable cities, smart cities, urban computing and ICT. The term 'smart sustainable city', although not always explicitly discussed, 'is used to denote a city that is supported by a pervasive presence and massive use of advanced ICT, which, in connection with various urban domains and systems and how these intricately interrelate, enables cities to become more sustainable and to provide citizens with a better quality of life.' (Bibri and Krogstie 2017a, p. 14). Here advanced ICT is associated with ICT of various forms of pervasive computing, as we will elucidate in the next paragraph. Further, 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 the new wave of computing, which is conceptualized as an enabling, integrative, and constitutive technology and thus regarded as a powerful driver for environmental, social, and economic development due to its transformational effects in relation to urban sustainability.

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). The increasing convergence of urban ICT of various forms of computing is increasingly seen as a way to capture further and invigorate the application demand for the diverse solutions for urban sustainability that emerging and future ICT can offer. The ability of computerizing all the systems and domains of cities to improve sustainability constitutes an indication of the reach of the gravitational field of ICT of the new wave of computing's effort to develop innovative solutions and sophisticated approaches from the ground up for smart sustainable cities of the future (Bibri and Krogstie 2016a). Therefore, the potential of monitoring, understanding, probing, and planning cities through advanced ICT can well be leveraged in the improvement of sustainable urban development (Bibri and Krogstie 2016a, 2017a). Indeed, smart cities (e.g. Al Nuaimi et al. 2015; Batty et al. 2012) and sustainable cities (e.g. Bibri and Krogstie 2016a; 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. In becoming complex systems par excellence, smart sustainable cities rely more and more on sophisticated technologies and their applications to realize their potential for responding to the challenge of sustainability. The most prevalent of these technologies and their applications, which are prerequisite for realizing ICT of the new wave of computing, are UbiComp, AmI, the IoT, and SenComp and related big data analytics and context–aware computing in relation to the domain of smart sustainable urban development (e.g. Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2016a, 2017a; Böhlen and Frei 2009; Shepard 2011; Solanas et al. 2014). Big data analytics and context–aware computing as rapidly growing areas of ICT are becoming important to the functioning, planning, and development of smart sustainable cities (Bibri and Krogstie 2016b). Therefore, the expansion of these computing approaches are increasingly stimulating the development of other models of smart sustainable city as urban initiatives and projects, such as smarter cities and smart cities incorporating sustainability.

5.4.2. Smarter Cities

Like smart sustainable cities, 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 urbanites and other urban entities. Accordingly, the conceptualization of smarter cities is associated with the ever–growing and deep embeddedness of advanced ICT into the very fabric of contemporary cities in terms of operations, functions, designs, and services. It indeed differentiates smarter cities as emerging and future cities from the conceptualizations of early faces of smart cities. According to Su, Li and Fu (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. 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.' Chourabi et al. (2012) conceive of 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; Böhlen and Frei 2009; DeRen, JianJun and Yuan 2015; Kamberov 2015; Khan, Anjum and Kiani 2014; Khan et al. 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 big data and context–aware applications operating across cloud computing infrastructures can monitor what is happening in urban environments (in terms of situations, events, activities, processes, behaviors, locations, spatiotemporal settings, environmental states, socio–economic patterns, 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 healthcare, smart education, smart safety, smart planning, smart governance, or smart buildings—across many spatial scales (Bibri and Krogstie 2016b). Here, smartness should primarily be directed towards achieving the goals of sustainable development rather than the efficiency of smart solutions and the advancement of technology.

5.4.3. Smart Cities Incorporating Sustainability

In essence, there are two mainstream approaches to smart city: (1) the technology and ICT–oriented approach and (2) the people–oriented approach (see Bibri and Krogstie 2017a for an overview). 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 emphasize the soft infrastructure and people, i.e. social and human capital in terms of knowledge, participation, equity, safety, and so forth (Angelidou 2014). Also, the 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, real–time cities, energy–efficient cities, amongst many other nomenclatures, as well as hybrid cities which combine two or more of these names (Bibri and Krogstie 2017a). While some smart cities have the tendency to explicitly incorporate the goals of sustainability, ICT is sometimes used in other smart cities without making any contribution to sustainability (Bibri and Krogstie 2017a). The focus in this paper is on the smart city definitions that tend to integrate the concept of sustainability. In these definitions, the emphasis is on the role of human and social capital as well as new technologies in improving economic, social, and environmental sustainability in smart cities (e.g., Batty et al. 2012; Giffinger et al. 2007; Nam and Pardo 2011; Neirotti et al. 2014; Toppeta 2010). It is important to note that the early smart cities incorporating the goals of sustainable development are not associated with ICT of any particular form of pervasive computing. They tend to focus on specific technologies and their potentials and opportunities in terms of bringing advanced solutions for diverse complex problems related to certain urban domains as well as for a number of online and mobile services to citizens to improve the quality of their life (Bibri and Krogstie 2017a). In short, while ICT progress is rapid and manifold, it seems to happen ad hoc in the context of the smart cities integrating sustainability when new technologies and their applications become available, rather than grounded in a theoretically and practically focused form of pervasive computing (see Bibri and Krogstie 2017a). In more recent years, however, such cities (e.g.Al Nuaimi et al. 2015; Solanas et al. 2014) have started to include the IoT and AmI technologies and their big data and context–aware applications as a way to contribute to sustainability.

However, a smart city incorporating sustainability denotes an urban innovation founded 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 in line with the goals of sustainable development. One of the most cited definitions in this regard is the one advanced by Caragliu, Del Bo and Nijkamp (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 broad understanding by what it entails in terms of the complementary nature of these dimensions. Though it doesn’t 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 meaning 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. 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, p. 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 have endeavored in recent years to amalgamate advanced technologies and their applications with urban planning approaches to come up with innovative and smart solutions that contribute to improving livability and enhancing sustainability (see Bibri and Krogstie 2017a). Smart initiatives have recently been used to promote environmental sustainability (e.g. Kramers et al. 2014; Neirotti et al. 2014), which implies that sustainability has not been an integral part of all the definitions of smart city.

6. Merging Technologies and Applications of Models of Smart Sustainable City With Typologies and Design Concepts of Models of Sustainable Urban Form to Improve Urban Sustainability

The shaping role and influence of ICT of the new wave of computing—considering its constitutive nature and transformative impact—will grow even more in contemporary 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 several 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 are ushering in automation and intelligence in nearly all the systems and domains of sustainable cities (e.g. Bibri and Krogstie 2016a, 2017a), thereby finding applications in virtually all spheres of urban sustainability. Combined, they can be utilized in such diverse urban domains as energy, environment, transport, mobility, healthcare, education, public safety, design, planning, economic forecasting, but to name a few. 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 well associated with, and even exceed, 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 (ecological design) as important strategies through which sustainable urban forms can be achieved. Of importance to underscore is that these themes are distilled based on several studies carried out over the past 25 years or so within the area of sustainable urban planning.

By linking these themes to the effects of big data and context–aware applications on sustainability, it becomes evident that there is tremendous potential to advance the contribution of sustainable urban forms to the goals of sustainable development—with 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 2017a). 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 (discussed in more detail below).

The proposed matrix (see Table 3) 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, which smart sustainable cities rely on the fulfillment of the associated ICT visions. The themes are the criteria of the proposed matrix. An option of big data application (BDA), context–aware application (CAA), or both (BDCAA) is assigned to each cell of the matrix to express the link between each form of pervasive computing (i.e. UbiComp, AmI, the IoT, and SenComp) and each theme associated with typologies and design concepts. Both themes and applications are the outcome of thematic analysis. As Table 3 shows, one theme may involve four technologies. The rationale is that the application areas of these technologies differ or overlap in terms of how they relate to that theme or contribute to various aspects of it. Regardless, this variation or overlay serves the same purpose in terms of sustainability effects. Accordingly, one big data or context–aware application may offer different solutions associated with one theme. In addition, big data and context–aware applications tend to appear across different typologies and design concepts. The rationale is that either one of these two applications relates to a given urban domain (or subdomain), which may entail different typologies and/or design concepts, adding to the fact that each class of applications is associated with various urban domains and subdomains. For example, for increasing urban sustainability by combining traditional and modern architecture, AmI–based networks and information processing platforms (using context–aware applications) control traffic, energy, environment, waste, and water (Böhlen and Frei 2009)—several cities (e.g. Masdar, Dongtan, and Hammarby Sjöstad) implementing new technologies are seen as idyllic 'ecological solutions' (Rapoport and Vernay 2011).

The use of big data analytics and context–aware computing in conjunction with urban typology and design will play a significant role in realizing the key aspects of the improvement of the contribution of sustainable urban forms to sustainability. This improvement relates to 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 at the core of the other use of big data analytics, as we will elucidate in the next section.

The smart sustainable urban form matrix in Table 4 provides insights into how sustainable urban forms can improve their contribution to sustainability with 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 or field work. Important to note is that the field of smart sustainable urban forms is in its very early stages (Bibri and Krogstie 2017b), so too is the field of smart sustainable cities (Bibri and Krogstie 2017a). This is indeed a new techno–urban phenomenon, and thus the term only became widespread during the mid–2010s (e.g. Al−Nasrawi, Adams and El−Zaart 2015; Bibri and Krogstie 2016a, 2017a; Höjer and Wangel 2015; Kramers, Wangel and Höjer 2016; Rivera, Ericsson and Wangel 2015). This implies that there are no concrete case studies to investigate or explore, nor is there a fair amount of scholarly research done with respect to smart sustainable cities and urban forms. In particular, no study has been conducted on the topic of smartening up sustainable urban forms—according to a recent literature review carried out by Bibri and Krogstie (2017a). 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 smartness. 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 innovation with the agenda of sustainable development, thereby justifying ICT investments by environmental concerns and socio–economic needs.

Although this paper 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 the merger of UbiComp, AmI, the IoT, and SenComp technologies in an increasingly technologized and computerized urban society, as such technologies evolve over time and become widely deployed across urban environments.

Typologies and Design Concepts (Themes)

Energy savings	BDCAA	CAA	BDA	CAA

Accessibility to services and facilities	BDCAA	CAA	BDA	CAA
Emissions reduction	BDCAA	CAA	BDA	CAA
Quality of life (social interaction)	CAA	CAA		
Energy conservation	BDCAA	CAA	BDA	CAA
Air pollution reduction	BDCAA	CAA	BDA	CAA
Transport and travel reduction	BDCAA	CAA	BDA	CAA
Social interaction	CAA	CAA		
Traffic congestion and air pollution reduction	BDCAA	CAA	BDA	CAA
Public safety	BDCAA	CAA	BDA	CAA
Traffic congestion and air pollution reduction	BDCAA	CAA	BDA	CAA
Social and cultural integration	CAA	CAA		
Transport operation and energy efficiency	BDCAA	CAA	BDA	CAA
Mobility and accessibility need balancing	BDCAA	CAA	BDA	
Emissions and waste reduction	BDCAA	CAA	BDA	CAA
Travel costs reduction	CAA	CAA		
Vibrant economy and desirable quality of life	BDCAA	CAA	BDA	
Air pollution reduction	BDCAA	CAA	BDA	CAA
Health benefits	BDCAA	CAA	BDA	
Urban image and economic attractiveness	BDCAA	CAA	BDA	CAA
Reducing the demand for energy	BDCAA	CAA	BDA	CAA
Influencing heating and cooling processes	CAA	CAA		CAA
Influencing building heat gains and losses	CAA	CAA		CAA
Traffic and air and noise pollution reduction	BDCAA	CAA	BDA	CAA

Density UbiComp AmI IoT SenComp
Compactness Mixed–land UseDiversitySustainable TransportGreening Passive Solar Design

Table 4. Smart sustainable urban form matrix: Improving the contribution of sustainable urban forms to sustainability.

7. Evaluation of the Contribution of Sustainable Urban Forms to Sustainability

7.1. The Untapped Potential of Big Data Analytics and Simulation Models

ICT of the new wave of computing can provide unparalleled (data–driven) methods that enable to understand and analyze the nature of complex urban phenomena and dynamics in the context of sustainable urban forms. This is invaluable for evaluating, forecasting, and thus planning the future of such forms, in particular in relation to 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, 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 build advanced simulation models necessary for gaining predictive insights into the progressive and shifting patterns of this contribution that can aid in making strategic decisions and forecasting future problems. Urban ICT, as a by–product of its normal operation—on the basis of big data analytics and simulation models and what they entail in terms of pervasive sensing, data processing, cloud computing, and wireless and mobile networking, allow for collecting and integrating massive repositories of spatiotemporal data pertaining to urban structures, organizations, and forms. Such repositories can be utilized for monitoring, understanding, analyzing, and planning sustainable urban forms in ways that strategically evaluate and enhance their contribution to sustainability, among other things. 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 iterate. Consequently, big data movement is gaining increased momentum and worldwide attention in the urban domain. This is being fueled and boosted by the intensive R&D within ICT of the new wave of computing 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 as well as related intelligence functions and simulation models. The rationale for this pursuit is the underlying benefits of the striking analytical power of big data in relation to the different dimensions of the sustainability of cities, among other things.

7.2. Big Data Analytics as An Alternative to Traditional Data Collection and Analysis Methods for Investigating Sustainable Urban Forms

In addition to its uses in all urban domains and systems of sustainable urban forms, big data analytics can accelerate and improve how data can be collected, processed, analyzed, modeled, and simulated in the research domain of urban sustainability, especially in relation to evaluating whether and to what extent sustainable urban forms contribute to the goals of sustainable development and what can be done to strategically enhance this contribution. As an alternative to traditional data collection and analysis methods, which have been used for over two decades to study sustainable urban forms, big data analytics driven by the IoT is changing the whole research paradigm, shifting from collecting data manually and examining and reflecting on these data to relying on advanced analytics, in addition to 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 participatory and non–participatory endeavors. These issues have in fact for 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 and methods of sustainability in the urban domain. Many studies (e.g. Breheny 1992a; Cervero and Kockelman 1997; Cheng et al. 2013; Gibbs, Longhurst and Braithwaite 1998; Kärrholm M. 2011; Jabareen 2006; Neuman 2005; Williams, Burton and Jenks 2000) investigating, or referring to other research work carried out on, the correlation between travel behavior, walking, cycling, car driving, and other determinants 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. These studies tend to generate non–conclusive, weak, limited, unreliable, conflicting, or uncertain findings.

7.3. The Role of Big Mobility Data in Evaluating the Environmental and Socio–Economic Performances of Sustainable Urban Forms.

Evaluating and forecasting the built form (buildings, streets, residential and commercial areas, public and green infrastructure, neighborhoods, districts, 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.

7.3.1. 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. These novel assessment practices can provide robust results and novel insights into whether and to what extent 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, processing, and analyzing real–time mobility data and data from large–scale and open datasets that can simultaneously record, calibrate, and visualize environmental performance as to GHG emissions deriving from energy consumption related to dynamical traces of different kinds of mobility patterns and forms (and travel behaviors) in relation to the typologies and design concepts of sustainable urban forms and their combination across many spatial scales in different locations. Likewise, to iterate, previous studies attempting to find correlations between environmental sustainability and some typologies 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, or conflicting findings (see, e.g. Bibri and Krogstie 2017a; Jabareen 2006; Neuman 2005; Williams, Burton and Jenks 2000).

7.3.2. 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 socio–economic 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 and forms 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 socio–economically 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 socio–economic 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 the structure of social networks (sustaining long–lasting friendships, establishing new social and professional links, initiating face–to–face conversations, etc.). What is known 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 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 (social) sustainability. A key theme in debates on compactness and diversity is the promotion of the quality of life through social interactions (Wheeler 2002; Williams, Burton and Jenks 2000). In light of this, big mobility data analytics can play an important role in understanding complex urban phenomena related to other aspects of the built environment favored by sustainable urban forms. Indeed, research within the area of big data analytics pertaining to social networks should extend its focus beyond the social space, tackling 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 and from one location to another despite the similarity of demand profiles driven by how transport systems and networks are connected within the different typologies of sustainable urban forms. Currently related explanations are extremely weak and ICT of the new wave of computing (namely big data analytics and context–aware computing) is expected to provide dramatically new data sets and predictive models that will disentangle many intractable issues concerning the link between different forms of mobility and transport and socio–economic performance specific to the topographic and design features 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 indeed o 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 like satellite–enabled sensing for collecting mobile communication detail records and the GPS and RFID tracks as dynamical traces of social interactions and individual mobility patterns; 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 for strategically planning sustainable urban forms and the combination of the underlying typologies and design concepts in relation to different spatial scales in terms of the associated socio–economic (and environmental) performance in the context of sustainability. Indeed, these models as representation of operating urban systems on a small or medium scale allow urban administrators to predict how changes in those systems would affect other parts of the systems or operations.

7.3.3. Big Data: The Basic Ingredient for the Next Wave of Sustainable Urban Form Analytics

The fundamental ingredient for the next wave of urban analytics that is rapidly gaining momentum is big data sets pertaining to human mobility, fostered by the ubiquity presence or widespread diffusion of sensor, information processing, and wireless communication technologies. These technologies, as a by–product of their normal operation, allow for collecting, coordinating, and analyzing colossal repositories of spatiotemporal data representing city–wide proxies for human mobile movements and activities of both individual and collective kind. The massive data repositories pertaining to human mobility will be the determinant of the future form of 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 urban 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 (see Bibri and Krogstie 2017b). Thus far, several international project '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 patterns, energy usage patterns, traffic patterns, climate patterns, social interactions, accessibility patterns, economic networks, and so on. Undeniably, big mobility data analytics are, to iterate, more suitable and effective than traditional data collection and analysis, such as surveys, interviews, participatory and non–participatory 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. 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. Unsurprisingly, 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. We consider that future ICT—given the unique foundation of its application on data and complexity sciences—will provide us with dramatically new data sets and 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 functioning, and behavior and activity identification related to certain typologies across several spatial scales.

The impetus of using big data analytics as an alternative to traditional data collection and analysis method and beyond is the ease 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. These can be deployed on a city–wide scale for many purposes. In particular, the strategies through which sustainable urban forms can be achieved entail many features of highly pertinent correlations with variables of mobility patterns in relation to energy, traffic, transport, travel, climate, and accessibility patterns and other complex urban dynamics 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, and ecological facets of the typologies and design concepts 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 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). Big mobility data (vast amount of mobile 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 towards 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.

7.4. Urban Simulation Models: An Approach into Strategically Assessing and Enhancing the Contribution of Sustainable Urban Forms to Sustainability

The available big data technologies, techniques, tools, and algorithms should be able to allow to collect, process, and analyze the urban data to build powerful simulation urban models, with the primary aim being to gain predictive insights for strategic decision–making and action–taking purposes concerning urban operational functioning, planning, and design. This involves, among other things, the kind of decisions and actions associated with the strategic assessment and enhancement of the contribution of sustainable urban forms to the goals of sustainable development through devising and applying modeling approaches into rearranging, harnessing, or integrating different topographic and design features (e.g. sustainable transport and density, compactness and mixd–land use, and solar passive design and density) as well as urban domains (e.g. network performance, mobility and travel behavior, and urban land use and transport) in an optimal way, with the ultimate aim of enhancing environmental and socio–economic performances of such forms. This can be enhanced by simulation and prediction methods built on top of the mined models or patterns attained through knowledge discovery. One of the major scientific challenges to the development of smart sustainable urban forms is to, according to a recent literature review performed by Bibri and Krogstie (2017a, p. 25) '[t]o construct and aggregate several urban simulation models of different situations of urban life pertaining to the way…human mobility data can be linked to the spatial organizations, transport networks, travel behavior, socio–economic network performance, environmental performance, and land use of such forms. Also to explore and diversify the approaches to the construction and evolution of urban simulation models. This is to inform the future design of sustainable urban forms on the basis of predictive insights and forecasting capabilities.' The simulation process entails developing and analyzing digital prototypes of physical, behavioral, environmental, socio–economic, infrastructural, spatiotemporal, operational, and functional models and their synergic combination in relevance to sustainable urban forms to predict changes in their performance and forecast potential problems in the real world. Simulation denotes the operation of the whole model of the smart sustainable urban system (and its sub–systems) to evaluate the performance of the system, and allows to optimize that system to increase success and to adjust any parameters within the system being under investigation. This pertains in this context to the practicality of the typologies and design concepts of sustainable urban forms in terms of their sustainability performance, which can be affected by urban growth, urban dynamics, environmental pressures, socio–economic changes, urban trends or shifts, and other factors. These are new conceptions of the way such forms can operate and 'utilize the complexity [and data] sciences in fashioning powerful new forms of simulation model and optimization methods that generate urban structures and forms that improve sustainability, efficiency, equity, and the quality of life.' (Batty et al. 2012, p. 505). There is an evolving immediacy in the building of all kinds of urban simulation models 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 context of the real–time cities (e.g. Bibri and Krogstie 2017a). The prominence of urban simulation models in this context lies in aiding urban planners and architects in understanding under what conditions and in what ways the urban domains and systems (or some of their components) pertaining to sustainable urban forms fail to deliver at the level of sustainability and what to do about potentially predicted changes or forecasted problems, e.g. if there is a need to further enhance the integration and coupling of urban systems, to further reorganize and coordinate urban domains, and/or to create new 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 urban forms on the basis of predictive insights in ways that strategically assess and enhance their contribution to the goals of sustainable development.

8. Challenges

8.1. Coupling, Integrating, and Coordinating ICT of the New Wave of Computing and Merging it with Sustainable Urban Forms

The opportunities for smartening up (the redevelopment of) sustainable urban forms 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. 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 socio–economic 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 towards 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, information science, formal science, complexity science, and sustainability science) and city–related disciplines (e.g. urban planning, urban design, architectural design, urban sustainability, and sustainable urban development). 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 socio–economic 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 socio–economic urban issues. The smart sustainable urban form will be in the vanguard of this macro–shift or techno–urban change.

8.2. Big Data Analytics and Context–Aware Computing Technologies

The rising demand for big data analytics and context–aware computing as disruptive technologies signifies that there are major scientific and intellectual challenges that need to be addressed and overcome with regard to the design, development, and deployment of data–centric and smart applications within smart sustainable urban forms. These challenges are mostly computational and analytical in nature, including constraints of design science and engineering (e.g. Bibri 2015a; Bibri and Krogstie 2017b), data management and analysis, database integration across urban domains, privacy and security, data growth and sharing, data uncertainty and incompleteness, data quality, urban intelligence functions, urban simulation models (e.g. Al Nuaimi et al. 2015; Batty et al. 2012; Bertot and Choi 2013; Bibri and Krogstie 2017b; Demchenko et al 2013; DeRen, JianJun and Yuan 2015; Fan and Bifet 2013; Khan, Uddin and Gupta 2014; Kitchin 2014; Krogstie and Gao 2015; Malilk 2013; Mann 2012; Solanas et al. 2014; Townsend 2013), and modeling and management of contextual information in large□scale distributed pervasive applications and in open and dynamic pervasive environments (e.g. Bibri 2015a; Strimpakou et al. 2006). Adding to these technical challenges are the financial, organizational, institutional, and regulatory ones, which are associated with the implementation, retention, and dissemination of big data in relation to sustainable urban forms. In addition, controversies over the application and benefit of big data analytics relate to representativeness, limited access and related divide, and ethical concerns about accessibility (Fan and Bifet 2013). Nevertheless, by advancing the existing knowledge on the available processing, analysis, and management capabilities associated with big data analytics and context–aware computing in terms of conceptions, tools, principles, paradigms, methodologies, and risks, the goal of making sustainable urban forms smartly more sustainable as to their systems and domains and the underlying typologies and design concepts as well as related operations, functions, and services will be attainable (see Bibri and Krogstie 2017a). This entails though ensuring the current open issues stemming from those challenges are under investigation and scrutiny by the constituents of the technological innovation system of ICT of the new wave of computing for urban sustainability, namely industry consortia, entrepreneurial companies, universities, research institutes, sustainable development institutes, policy networks, and governmental agencies.

9. Conclusions

The debate over the ideal or desirable smart sustainable urban form has just began, and will undoubtedly continue in an increasingly technologized and computerized urban society. In the meantime, the concept of smart sustainable urban development will evolve as to developing different models of smart sustainable urban form based on crafting new and making creative combinations of typologies and design concepts—along with more effective ways to merge them with 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 spaces. Therefore, the contemporary urban computing and ICT research agendas are of significance and salience to sustainable urban forms. Sustainable urban forms need, however, to be well suited to the requirements of such agendas, particularly in relation to the ubiquity presence and massive use of ICT in urban systems and domains. Underlying emerging and future 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, and designs, 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 opportunities as to 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 towards 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 is of high relevance and importance to achieve the required level of sustainability with respect to urban operations, functions, services, and designs. This holistic approach holds great potential to rise to the challenge of sustainability 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 in relation to sustainability. The aim of this study was to explore and substantiate the real potential of ICT of the new wave of computing to evaluate and improve the contribution of sustainable urban forms to the goals of sustainable development. This entailed merging big data and context–aware technologies and applications with the typologies and design concepts of sustainable urban forms to achieve various objectives. Important to underscore first is that this study serves to facilitate collaboration among and between the academic disciplines of urban planning and design, sustainable development, sustainability science, and ICT for the primary purpose of generating the kind of interactional knowledge necessary for a more integrated understanding of the topic of smart sustainable urban forms (see Bibri and Krogstie 2017a). This is a core contribution that supports the foundational ethos of interdisciplinarity pertaining to smart sustainable urban planning and development. Further, this study focuses on three types of sustainable urban forms given their distinctive contribution to sustainability that have several overlaps among them in their concepts, ideas, and visions. These types are not mutually exclusive but rather compatible to a great extent. This implies that there still are some key differences and characteristic concepts for each one of them. Accordingly, 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, greening, and design coding. While both smart sustainable cities and smarter cities typically rely on the fulfillment of ICT visions of the new wave of computing, the smartness in the first case offer great prospects for smarter cities to achieve the required level of sustainability and the smartness in the second case is directed primarily towards advancing the contribution of smart sustainable cities to the goals of sustainable development. This entails strengthening the role of ICT, especially big data analytics and context–aware computing technologies and applications, in urban operations, functions, services, and designs as to management, planning, and development to improve sustainability, among other things.

As this paper shows, the three selected urban forms and cities are the most sustainable models and approaches. Different models and approaches use different scales of physical and technological concepts, as well as emphasize some of these concepts over others. In practice, sustainable urban forms and smart sustainable cities entail varied planning and design approaches. The question is, how such forms and cities can be merged in terms of their design concepts and typologies and their technologies and applications, respectively? This paper outlines a distinctive set of three design concepts and four typologies as well as four technologies and 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, as well as a data–driven approach and simulation method that can advance the assessment practices of such forms. 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 paper concludes that by using the relevant advanced technologies and their 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 paper 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 technologies and 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 smartly 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 the technologies and applications of smart sustainable cities 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 2017a; Jabareen 2006).

Furthermore, this study indicates that there are many challenges ahead to tackle, just as there are many fascinating opportunities ahead to embrace in the realm of smart sustainable urban forms. These challenges need to be overcome in order for sustainable urban forms to realize their full potential as to evaluating and improving their contribution to sustainability. While enormous challenges exist as to deploying UbiComp, AmI, the IoT, and SenComp technologies, implementing their novel applications, putting in place new digital technologies that can couple, integrate, and coordinate such technologies and their applications, and merging the whole informational landscape with the typologies and design concepts of sustainable urban forms, the effort is definitely worth the outcome, especially in an unequivocally increasingly technologized and computerized urban society. That is to say, the resulting blend of the most advanced solutions and sophisticated approaches enabled by constellations of heterogeneous instruments across many spatial scales of sustainable urban forms will provide a fertile environment for smartening up sustained urban development, which will in turn be conducive to achieving urban sustainability as a long–term goal. With the advancement of knowledge on ICT of the new wave of computing (and thus big data analytics and context aware computing) in terms of conceptions, techniques, paradigms, principles, methodologies, and risks, the goal of advancing sustainable urban forms by making them smartly more sustainable will be attainable and worthy (see 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 smart and data–centric applications that will effectively evaluate and 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 all forms of computer 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 intelligence functions and related simulation models, optimization methods, and efficient services. This will eventually form a techno–urban digital ecosystem that is conducive to improving the long–term environmental and socio–economic health and efficiency of sustainable urban forms and enhancing the quality of life of their dwellers.

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Authors' Contributions

SEB and JK have both made substantive intellectual contributions to the study. They have made substantial contributions to the collection and analysis of data, have been involved in drafting the manuscript and revising it critically for important intellectual content; and have given the final approval of the current version to be published.

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Before starting his PhD studies, SEB served as a sustainability and ICT strategist, business engineer, and consultant. Over the past few years, he has been involved in a number of research and consulting projects pertaining to green ICT strategy, urban big data and context–aware computing, strategic sustainability innovations, sustainable business model innovation, clean technology, sustainable urban development, and green entrepreneurship and innovation.

SEB's current areas of research work include smart sustainable cities, Ambient Intelligence (AmI), Ubiquitous Computing (UbiComp), Sentient Computing (SenComp), the Internet of Things (IoT), as well as how these ICT visions of pervasive computing relate to urban design and planning, urban sustainability, efficiency of urban operations and services, and the quality of life of citizens, in addition to their core enabling technologies, namely sensor technologies, data processing platforms, cloud computing infrastructures, middleware architectures, and wireless communication networks.

SEB has a genuine interest in interdisciplinary and transdisciplinary research. In light of his varied academic background, his research interests include pervasive computing paradigms or ICT visions (i.e. AmI, UbiComp, SenComp, and the IoT), urban computing, urban informatics, big data analytics, context–aware computing, urban sustainability, sustainable city models (eco–city, compact city, green city, new urbanism, etc.), smart city approaches (knowledge city, energy–efficient city, ambient city, ubiquitous city, sentient city, real–time city, etc.), sustainability transitions and eco–innovations, green and social innovation of technology, philosophy and sociology of scientific knowledge, social construction and shaping of science–based technology, governance of sociotechnical changes in technological innovation systems, energy efficiency technology, sustainable business model innovation, and technology and innovation policy.

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

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The issue of sustainable urban form has been problematic and difficult to deal with, and therefore there are still significant challenges that need to be addressed and overcome.

Sustainable urban forms need to embrace and leverage what ICT has to offer as innovative solutions and sophisticated methods so as to thrive—i.e. advance their contribution to sustainability.

The field of sustainable urban planning is required to extend its boundaries and broaden its horizons beyond the ambit of the built form of cities.

There exist four technologies and two classes of applications pertaining to models of smart sustainable city that can be merged with the typologies and design concepts of models of sustainable urban form.

The proposed Matrix helps scholars and planners in understanding and analyzing how the contribution of sustainable urban forms to sustainability can be improved through big data analytics and context–aware computing.

The proposed data–driven and simulation methods are intended to evaluate and strategically enhance the contribution of sustainable urban forms to the goals of sustainable development.