Big Data and Context–Aware Computing Applications for Smart Sustainable Cities

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Abstract. Information processing is increasingly embedded in the systems and processes of the contemporary city to enhance its operations, functions, and designs. This has been fueled by the new digital transition in ICT enabled by an integration of various forms of pervasive computing. Driving this transition predominantly are big data analytics and context–aware computing and their increasing amalgamation in a number of urban application domains, especially when such analytics and computing share the same enabling technologies, namely pervasive sensing devices, computing infrastructures, data processing platforms, and wireless communication networks. The purpose of this paper is to outline the key technological components of big data and context–aware computing, to demonstrate the opportunities and applications computing has to offer, and to identify the challenges it poses in the context of smart sustainable cities. We argue that combining big data analytics and context–aware computing can be leveraged in the advancement of urban sustainability, as their effects in this regard reinforce one another as to their efforts for transforming urban life by employing the data–centric and smart applications and services to improve, harness, and integrate urban systems as well as facilitate collaboration among urban domains.

1 Introduction

As complex systems, cities with their systems and domains becoming more interconnected and integrated and their processes being highly dynamic, rely more and more on sophisticated technologies to realize their potential as to responding to and rising to the challenge of sustainability. Among these technologies are big data analytics and context–aware computing, which are rapidly gaining momentum and generating worldwide attention in the realm of smart sustainable urban development (e.g., [1] [2]

[3] [4] [5]). Big and context data constitute fundamental ingredients for the next wave of urban analytics and planning. Especially, there is a variety of potential uses of big data and context–aware computing to address urban sustainability from the source thanks to deep insights and intelligent decision support through data mining, machine learning, business intelligence, modeling, simulation, and prediction. This points to new opportunities and alternative ways to construct and operate future cities.

Smart sustainable cities typically rely on the ICT visions of the new wave of computing, a combination of various forms of pervasive computing, where everyday objects and entities communicate with each other and collaborate across heterogeneous environments to provide information and services to citizens and other urban stakeholders. The prevalent forms of pervasive computing are Ubiquitous Computing (UbiComp), Ambient Intelligence (AmI), the Internet of Things (IoT), and Sentient Computing (SenComp) (see [6] for a detailed overview). Context–aware behavior and big data capability are seen to be prerequisites for realizing pervasive computing applications and systems pertaining to UbiComp, AmI, SenComp, and the IoT (e.g., [5] [7] [8] [9]).

Context–aware applications and systems hold great potential to enhance urban operational functioning and services in terms of sustainability, efficiency, and the quality of life. Indeed, the use of context aware technologies in the urban context involves a wide variety of urban applications. This entails that the city takes the form of constellations of context–awareness architectures, platforms, and applications across several spatial scales, connected through wireless networks, which collect, process, analyze, and reason about real–time data regarding urban life in relation to the underlying operating and organizing systems and processes to generate inferences (situations, events, locations, environmental states, spatiotemporal settings, etc.) for decision–making processes. Hence, context–aware computing is a key component of the smart (and) sustainable cities infrastructures. Having access to context information in smart (and) sustainable city applications and systems plays a key role in supporting decision–making processes (e.g., [4] [5]). It is becoming increasingly evident that smart urban environments based on context–aware technologies will be commonplace in cities in the near future to support urban living in many ways (e.g., [10] [11]).

The notion of big data and its application in urban analytics has attracted great attention over the past few years. The big data paradigm is fundamentally changing the way the city functions, driving decision–making and service delivery within several domains. The digital data are projected to grow from 2.7 Zettabytes to 35 Zettabytes by the year 2020 [12]. Big data is the next huge step for the urban world. Around the city, an exponentially growing amount of data continues to be generated beyond imagination and the sheer volume of information that is already available out there, coming from different urban domains, is at such high value that it would be astute for urban planners and strategists in collaboration with ICT experts to exploit it for improving urban sustainability. Indeed, big data provide fascinating opportunities to change how things can be done in cities in terms of operation, management, and planning from a sustainability perspective. Unsurprisingly, big data have become a new catchphrase in the ambit of smart sustainable cities, and big data analytics as a general area applied to various urban domains has become of prime focus in the research field thereof. Big data analytics is associated with a wide variety of intelligent applications and services pertaining to different dimensions of urban sustainability. Unquestionably, its main strength lies in the high influence it will have on many facets of smart sustainable cities and their citizens (e.g., [2][3][4]).

Despite the recent increase of research in big data in relation to city analytics and in context awareness in relation to interactive applications in urban spaces, the bulk of work tends to deal largely with applications and services in the realm of smart cities, leaving important questions involving to what extent and in what ways can big data and context–aware computing add to the dimension of sustainability in the ambit of sustainable cities barely explored to date. In addition, a new research wave has started to focus on how to enhance smart city approaches as well as sustainable city models by combining these two urban development strategies in an attempt to achieve the required level of the urban operational functioning, efficiency, and planning in line with the goals of sustainable development [1]. One implication of this endeavor is that big data and context–aware computing is being given a prominent role, and the evolving data–centric holistic approach is seen to hold great potential to address the challenge of urban sustainability under what is labelled 'smart sustainable cities.'

2 Conceptual Background

2.1 Smart Sustainable Cities

Smart sustainable city is a new techno–urban phenomenon. So, the term only became widespread during the mid–2010s [1] as a result of several intertwined global shifts. The concept has emerged on the basis of five different developments, namely sustainable cities, smart cities, ICT, sustainable urban development, sustainability and environmental issues, and urbanization and urban growth [13]. 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 efficient and to provide citizens with a better quality of life. A smart sustainable city is defined as 'an innovative city that uses…ICT 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.' [14].

2.2 Big Data Analytics/Computing

'Big data' is an evolving term that is used to describe the growth, proliferation, diversification, heterogeneity, complexity, availability, and utilization of datasets, which existing data processing applications and platforms are inadequate to handle. This implies that big data encompass the use of tools and techniques that work beyond the limits of normal data analytics methods involving storage, capture, retrieval, integration, processing, analysis, and visualization for timely and accurate decision–making purposes. There are many definitions of big data, and they tend to offer different, yet related, perspectives of the concept, attempting to capture various strands for complementary purposes. Big data is defined as 'a high–volume, high–velocity and high–variety information assets that demand cost–effective, innovative forms of information processing for enhanced insight and decision–making.' [2] While there is still a lack of agreement about the definition of big data, there seems to be consensus that big data will lead, with projected advancements, to immense and fascinating opportunities in the coming years.

Big data can be characterized by what has come to be known as Vs. The main of which—identified as the most agreed upon Vs—include volume, variety, and velocity [15]. Additional Vs include veracity, validity, value, and volatility. The emphasis in this paper is on the main characteristics of big data: the huge amount of data, the velocity at which the data can be processed, and the wide variety of data types.

- Volume denotes the amount of the data generated from a variety of sources that are to be analyzed, amounting to terabytes, petabytes, exabytes, and zettabytes of data.
- Variety covers the diversity of data types, such as relational tables and databases, social posts, mobile records, video, audio, images, and web content, i.e., variety of structured, semistructured, and unstructured data.
- Velocity signifies the speed or pace at which the data flow from various 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.

In the urban context, the term 'big data analytics' refers to a collection of sophisticated and dedicated software applications run by powerful machines, which can turn large amount of urban data into intelligence for decision–making processes in relation to various urban domains. Generally, big data analytics relies on a combination of several technologies, including data mining, business intelligence, and statistical applications [16]. The analysis category that is most used in the urban domain is data mining. In this context, big data analytics targets optimization and intelligent decision support for control, management, and planning purposes through the implementation of optimization strategies and decision–taking processes in relation to a wide variety of urban application domains, such as transport, traffic, environment, energy, land use, health, and education.

2.3 Context–Aware Computing

As a fundamental aspect of everyday life, context shapes, influences, and changes the patterns underlying the interaction of all kinds of intelligent entities, e.g. humans, computers, and engineered systems, with their environment. Context–aware computing has been researched extensively by the HCI community since the late 1990s (e.g., [17] [18] [19]). 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' [1] by enabling computationally augmented environments to provide the most efficient services by relying on contextual information and thus anticipating and responding intelligently to diverse needs accordingly in a seamless and unobtrusive way. This applies particularly to new emerging faces of cities, namely ambient, sentient, and ubiquitous cities as well as cities as an Internet of everything.

The concept of context aware computing has been expanded beyond the ambit of HCI applications to include urban applications, such as energy systems, transport systems, communication systems, traffic systems, power grid systems, healthcare systems, education systems, security systems, and so on [2]. Here the focus is on the physical, environmental, spatiotemporal, and socioeconomic aspects of the urban context. Therefore, the concept of context–aware computing is associated with the operational functioning of the city and the wellbeing of its citizens, that is, sustainability, efficiency and the quality of life. Here the context denotes, drawing on [20], the environmental states and settings within the urban landscape that determine systems or applications' behavior. And the contextual variables provided by the smart sustainable cities infrastructures are understood as a means to understand the living environment of citizens anywhere at any time in the city. Hence, by properly using all kinds of contextual information about diverse urban variables, citizens can benefit from applications and services that automatically adapt to discovered context by changing their behavior accordingly.

2.4 Context Awareness in the Urban Domain

As a form of computation performed to generate inferences from context data for decision–making, context awareness is a central issue to ICT of the new wave of computing in the sense that it is given a prominent role in the notion of intelligence in relation to diverse application domains. In the urban context, the notion of intelligence entails that the urban environment recognizes situations, events, states, settings, and behaviors and intelligently reacts to them, anticipating and responding to different needs in urban spaces. To establish context awareness functionality requires to collect, aggregate, fuse, process, analyze, interpret, and propagate contextual information to support decision–making needs and to control over processes and provide services. This employs a wide variety of technologies, including sensor networks, machine learning methods, hybrid modeling and reasoning techniques, intelligent agents, cloud computing platforms, wireless communication networks, and middleware infrastructures [8].

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 an entity (e.g. transport system, traffic system, energy system, information system, etc.) that can be integrated (sensed, conceptualized, and modeled) in the design and development of a given application. Originated in pervasive computing the term 'context awareness' is used to describe technologies that are 'able to sense, recognize, and react to contextual variables, that is, to determine the actual context of their use and adapt their functionality accordingly or respond appropriately to features of that context.' [8]. In more detail, as a sensor–based perception, context awareness refers to an application–specific trait that indicates that computer systems (HCI and urban applications) are able to acquire information about the different aspects of the relevant context (physical, environmental, spatiotemporal, socioeconomic, behavioral, etc.) for further processing, analysis, and interpretation to generate high–level abstractions of context using machine learning and reasoning or hybrid modeling approaches to support intelligent decision–making and action–taking processes with respect to the efficiency, management, and improvement of urban systems.

3 Big Data and Context–Aware Computing Components for Smart Sustainable Cities

Like other application areas to which big data and context–aware computing is applied, smart sustainable cities require big data and context–aware components to be put in place across several spatial scales in the form of advanced enabling technologies necessary for designing, developing, and deploying the diverse applications and services that support urban sustainability. The technological components of big data analytics and context–aware computing required for smart sustainable cities encompass data processing platforms, pervasive sensing, wireless communication technologies and smart network infrastructures, advanced algorithms and techniques, privacy and security mechanisms, open standards and standard rules (see [2] [4] for a detailed account). For an overview of essential underpinning computational and conceptual tools for understanding how context–aware computing operates in relation to urban operational functioning for improving performance and efficiency as well as in relation to urban service delivery for enhancing the quality of life in the ambit of smart sustainable cities, the reader is directed to [2]. Among the key themes addressed in their work include context data processing and modeling, sensor observations and dynamic urban models, a framework integrating key dynamic models and analytic methods, the process of recognizing situations of urban life, and a basic multilayered architecture of context data processing.

4 Big Data and Context–Aware Computing Opportunities and Applications

The application of big data analytics and context–aware computing in smart sustainable cities offers clear prospects for achieving enhanced levels of sustainability in terms of efficiency, planning, and the quality of life. One of the core ideas underlying the use of such advanced technologies is to integrate solutions and facilitate collaboration across applications and services to have better and effective utilization and management of resources and infrastructure, more astutely strategic development, and more efficient and faster urban services. Accordingly, combining big data and context–aware applications has the potential to serve many urban domains and systems and how they interrelate in the context of sustainability.

Irrespective of what connotation smart sustainable cities can be based on, whether be it ambient, sentient, ubiquitous, or an Internet of everything, or a combination of some or all of these urban constructs, such cities are said to denote urban spaces loaded with clouds of data intended to shape the operational functioning and the experience of citizens of the city. Here, both context–aware computing and big data analytics are given a pivotal role, as all over the cities, big data and context–aware applications can monitor what is happening in urban environments, analyze, interpret, and react to them at varying ways and across several spatial scales. In contrast to the prevailing notion of smart cities of the future [3], which can 'be understood as a collection of plural research traditions, performed and commissioned by divergent actors all with their own motivation and implicit understanding of what a city is or should be' [10], the main motivation behind the concept and development of smart sustainable cities, based on big data and context–aware applications, is to advance urban sustainability by improving the contribution of cities to the goals of sustainable development. Indeed, being varied, the objectives of big data, in particular, are more in conjunction with the goals of big data urban stakeholders.

The prospect of smart and sustainable cities getting smarter is fast becoming the new reality [2], and this is opening up new opportunities for increasing their contribution to sustainability. This has been enabled 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, cloud computing models, and wireless and mobile networks, and, more recently, big data analytics. Subsequently, significant opportunities exist for UbiComp, AmI, the IoT, and SenComp in relation to modernizing the urban model in terms of different dimensions of sustainability. Indeed, the range of urban applications that utilize these new technologies in connection with sustainability is potentially huge, as these technologies—combined through what has been identified as big data and context–aware computing—usher in automation in nearly all urban domains. Efforts emanating from these technological fields transform and influence every aspect of urban life [11]. Accordingly, in view of their synergy and integration in terms of their functioning, UbiComp and AmI application areas include healthcare and social support, public services, learning and tele–working within the networked home, social groupings and community building, social inclusion, public safety, energy efficiency (smart buildings, smart transport, smart grid, smart planning, etc.), environmental monitoring, disaster management, transport and mobility, water and waste management, planning and design, and large–scale deployments in relation to smart cities. Likewise, the IoT application areas encompass environmental monitoring and protection (air and water quality and atmospheric conditions), urban infrastructure monitoring and management, waste management, energy management, medical and health systems, public safety, environment and disaster, building automation, natural ecosystems, transportation, and large–scale deployments in relation to smart cities. Overlapping with AmI, SenComp application areas involve transportation, safety and environmental impact, traffic and street light control systems, energy conservation, waste management, measuring and surveying buildings, civil security, and social and public services. Therefore, there is a lot to achieve with the deployment and implementation of these advanced solutions offered by ICT of the new wave of computing—if its potential is well focused on urban sustainability in terms of exploiting the benefits of big data and context–aware computing in the ambit of smart sustainable cities. Context awareness and big data technologies and their applications and uses play a significant role in realizing the key aspects of the improvement of the contribution of smart and sustainable cities to sustainability. The link between urban sustainability and big data and context–aware computing provides insights into understanding how urban ICT of the new wave of computing can add a whole new dimension to existing smart cities and sustainable cities.

Furthermore, the demarcation lines between UbiComp, AmI, the IoT, and SenComp pertain in large part to the kinds of applications they offer in relation to the urban sustainability domain, rather than to the core enabling technologies they normally share in terms of sensing, computing, and networking infrastructures. The underlying distinctions include the way in which the respective applications are used in connection with different urban domains, namely relying on context–aware computing, big data analytics, or a combination of these technologies. Regardless, combing these applications provide fascinating opportunities to advance smart sustainable cities in terms of the processes that operate and organize urban life: physical and spatial structures, infrastructure, administration, ecosystem services, and public services as regards to achieving the goals of sustainable development. Hence, the idea of coupling, integrating, and coordinating UbiComp, AmI, the IoT, and SenComp technologies and their novel applications is invaluable, if not necessary, at the level of (big data and context–aware) applications with regards to the advancement of urban sustainability.

Figure 1 shows the employment of the core enabling technologies of ICT of the new wave of computing to connect urban domains and systems to related applications and services in smart sustainable cities, using big data and context–aware computing. Urban domains and systems generate large amount of data, datasets and contextual data, as input for big data and context–aware applications, respectively, which in turn generate deep insights and inferences for decision–making processes to improve urban operational functioning, planning, and the quality of life in line with sustainability. Put differently, through pervasive sensing, computing, and networking infrastructures, big data and context–aware applications collect, store, manage, process, analyze, and model data pertaining to various urban domains and systems to discover new knowledge and generate context knowledge, respectively, to help decision–makers to improve urban performance and planning in relation to resources, infrastructures, networks, facilities, and services and their interrelationships in the context of sustainability.

For example, smart transport is associated with all ICT applications of the new wave of computing. That is, UbiComp, AmI, the IoT, and SenComp aim at improving all forms of transportation and mobility in cities. The IoT devices can assist in interconnecting various aspects of transportation systems (vehicles, infrastructure, drivers, roads, etc.) in terms of integrating communication, management, control, and information processing units across these systems, which results in smart traffic control, road assistance and safety, smart parking, logistic and fleet management, vehicle control, and toll collection systems [2]. AmI and UbiComp can substantially mitigate the negative impacts of transport on the environment triggered by saturated transport networks, endemic congestion, urban density, and community expansion by providing advanced forms of virtual mobility and thus curbing demand for actual one. AmI can moreover detect traffic patterns by analyzing real–time data, predicting traffic conditions, adjusting traffic controls to mitigate road congestion as well as reduce road accidents by opening new roads, enhancing transport infrastructure, and directing vehicles to alternative roads [4]. In addition, it provides advanced location–based services related to on–board navigation systems (using GPS) that allow, by means of multi–media presentations wirelessly transmitted and displayed on different kinds of devices, effective use of existing infrastructure and thus reduce energy consumption ad thus emissions by helping drivers to select cost– and time–efficient driving routes. Also, using GPS, information can be gathered and predictions be made regarding pollution density to generate localized air quality alerts. Furthermore, SenComp, AmI, and UbiComp can, at varying degrees, provide advantages associated with smart traffic lights and signals in terms of controlling the traffic flow in cities. This enhances their traffic patterns and transport systems, improves commuting, and handles high volume of traffic congestion by measuring different parameters of the traffic flow (the positions and speeds of cars, traffic speed and density, traffic conditions or jams, waiting time at the lights, etc.) using different types of sensors (GPS, loop sensors, remote sensors, etc.). Big data analytics enables 'data streaming to process and communicate traffic information collected through sensors, smart traffic lights, and on–vehicle devices to drivers via smartphones or other communication devices.' [4].

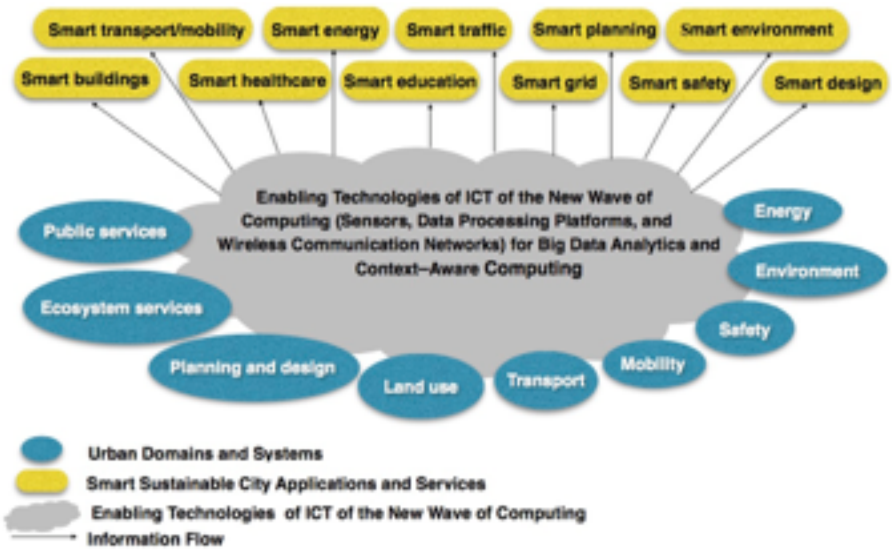

Fig. 1. Using the enabling technologies of ICT of the new wave of computing to connect urban domains and systems with related applications and services in smart sustainable cities

5 Challenges to Big Data and Context–Aware Computing

There are numerous challenges facing big data and context–aware computing that need to be addressed and overcome. These challenges concern the design, development, deployment, and implementation of related applications on a city–wide scale, from heterogeneous hardware components through to service delivery systems and application actions and from data through to mining, modeling, intelligence, simulation, and prediction with respect to the operational functioning and planning of smart sustainable cities. They are technological, computational, and analytical in nature, including data management, analysis, and mining; data(base) integration and networked–based coupling; urban simulation models and urban intelligence functions; privacy and security; and data proliferation, sharing, and quality (see [2] for a detailed account), in addition to organizational, financial, institutional, and regulatory challenges [4] [3]. By understanding, exploiting, and extending the available computational and analytical capabilities of, or advancing knowledge on, big data and context–aware computing in terms of conceptions, techniques, methods, principles, paradigms, and risks, great opportunities can be realized in terms of both improving and integrating urban systems as well as facilitating collaboration among urban domains through data–centric and intelligent applications and services in the context of smart sustainable cities. This entails ensuring that the open issues stemming from those challenges are under investigation and scrutiny by the socio–technical entities within the technological innovation system of big data and context–aware computing, namely industry consortia, business communities, research institutes, universities, policy makers and networks, and governmental agencies.

6 Conclusion

Big data analytics and context–aware computing are rapidly growing areas of ICT that are becoming ever more important to smart sustainable cities. Specifically, big data and context–aware computing and its uses will play a significant role in realizing the key characteristics of smart sustainable cities, namely operation and service efficiency, life quality enhancement, and intelligent management of natural resources and infrastructures. Indeed, huge expectations for gains are being placed on the ongoing research within big data analytics and context–aware computing. This is justified by the opportunities enabled by their amalgamation with regard to understanding, monitoring, analyzing, and planning smart sustainable cities to improve their contribution to sustainability. Worth noting is that their effects in this regard reinforce one another as to their efforts for transforming urban life by employing the data–centric and smart applications and services to improve, harness, and integrate urban systems as well as facilitate collaboration among urban domains.

Big data and context–aware applications have the potential to serve a wide variety of urban domains and add value to how their diverse components interrelate with respect to operation, management, and planning. Among the key smart applications and services enabled by big data and context–aware computing include smart transport, smart energy, smart environment, smart planning, smart design, smart grid, smart traffic, smart buildings, smart education, smart healthcare, and smart safety. Many cities in ecologically and technologically advanced nations have already started integrating big data and context–aware computing, actively engaging in smart sustainable initiatives and projects in the hopes of reaping sustainability benefits by developing and implementing data–centric and smart applications across urban environments.

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