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The emerging data–driven Smart City and its innovative applied solutions for sustainability: the cases of London and Barcelona

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Abstract

The big data revolution is heralding an era where instrumentation, datafication, and computation are increasingly pervading the very fabric of cities. Big data technologies have become essential to the functioning of cities. Consequently, urban processes and practices are becoming highly responsive to a form of data-driven urbanism that is the key mode of production for smart cities. Such form is increasingly being directed towards tackling the challenges of sustainability in the light of the escalating urbanization trend. This paper investigates how the emerging data-driven smart city is being practiced and justified in terms of the development and implementation of its innovative applied solutions for sustainability. To illuminate this new urban phenomenon, a descriptive case study is adopted as a qualitative research methodology to examine and compare London and Barcelona as the leading data-driven smart cities in Europe. This study shows that these cities have a high level of the development of applied data-driven technologies, but they slightly differ in the level of the implementation of such technologies in different city systems and domains with respect to sustainability areas. They also moderately differ in the degree of their readiness as to the availability and development level of the competences and infrastructure needed to generate, transmit, process, and analyze large masses of data to extract useful knowledge for enhanced decision making and deep insights pertaining to urban operational functioning, management, and planning in relation to sustainability. London takes the lead as regards the ICT infrastructure and data sources, whereas Barcelona has the best practices in the data-oriented competences, notably horizontal information platforms, operations centers, dashboards, training programs and educational institutes, innovation labs, research centers, and strategic planning offices. This research enhances the scholarly community's current understanding of the new phenomenon of the data-driven city with respect to the untapped synergic potential of the integration of smart urbanism and sustainable urbanism for advancing sustainability in the light of the emerging paradigm of big data computing. No previous work has, to the best of our knowledge, explored and highlighted the link between the data-driven smart solutions and the sustainable development strategies in the context of data-driven

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sustainable smart cities as a new paradigm of urbanism.

Keywords: Data-driven cities, Smart cities, Data-driven sustainable smart cities, Data-driven technologies, Applied solutions, Competences, Infrastructure, Urban systems and domains, Sustainability

Introduction

As predicated by the United Nations, more than half of the world's population live currently in urban areas, and around 70% will be concentrated in the cities by the year 2050. This anticipated urbanization of the world pose significant challenges related to environmental, economic, and social sustainability (e.g., Bibri 2018a, 2019a, 2020a; David 2017; Han et al. 2016; Estevez et al. 2016). Nevertheless, modern cities have a defining role in sustainable development and a central position in applying advanced technologies to support progress towards sustainability in the face of urbanization. In other words, sustainable smart cities, the leading paradigm of urbanism today, are seen as the most important arena for sustainability transitions in an increasingly urbanized world. They hold great potential to instigate major, and make significant contributions to, societal transformations by linking together the agendas of sustainable development and technological innovation.

However, in the current climate of the increased uncertainty and complexity of the world, it may be more challenging for smart cities to reconfigure themselves more sustainably and efficiently. This implies that the city governments in the technologically advanced nations will face significant challenges due to the issues engendered by urban growth. These issues include increased energy consumption, pollution, toxic waste disposal, resource depletion, inefficient management of urban infrastructures, ineffective planning processes and decision–making systems, saturated transport networks, endemic congestion, and social inequality and socio-economic disparity (Bibri and Krogstie 2017a, b). In a nutshell, urban growth raises a variety of problems that jeopardize the sustainability of cities, as it puts an enormous strain on urban systems as well as ecosystem services.

To disentangle these kinds of wicked problems, intractable issues, and special conundrums requires evidently major advancements of urbanism. In this respect, modern cities need to develop and implement more innovative solutions and sophisticated approaches underpinned by cutting–edge technologies and groundbreaking scientific knowledge. This is necessary to monitor, understand, analyze, and plan cities to improve sustainability, efficiency, resilience, equity, and the quality of life. Indeed, a number of alternative solutions based on advanced Information and Communication Technology (ICT) have materialized in recent years and are rapidly evolving, providing the raw material for how smart cities can enhance their performance with respect to sustainability in the face of the expanding urbanization (Bibri 2019b). In this respect, the IoT and big data technologies are seen as a key driver behind the emergence of smart cities (e.g., Ahmed et al. 2017; Batty et al. 2012; Hashem et al. 2016; Rathore et al. 2016, 2018) and sustainable smart cities (Bibri 2019a, 2019c, 2020a). It is estimated that 50 billion devices will be connected to the Internet by 2020 (Perera et al. 2014). Already, the number of objects connected to the Internet (e.g., computers,

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smartphones, WiFi-enabled sensors, wearable devices, household appliances, and many more) has, according to the Cisco report, exceeded the number of human beings in the world (Ahmed et al. 2017). The continuously increasing number of networked devices deployed across urban environments will in turn result in the explosive growth in the amount of the data generated. Therefore, big data analytics is increasingly seen to provide unsurpassed ways to address a range of rising environmental and socio–economic concerns facing modern cities. The multifaceted potential of ICT has been under investigation by the UN (2015) through their study on 'Big Data and the 2030 Agenda for Sustainable Development.' There is a general consensus that the potential of big data technology for the advancement of sustainability is still largely untapped, and a concerted action is needed to unlock and exploit this potential.

Big data technologies have become essential to the functioning of smart cities (e.g., Batty 2013; Kitchin 2014, 2015, 2016; Townsend 2013), particularly in their endeavor to improve their sustainability performance (Al Nuaimi et al. 2015; Hashem et al. 2016; Batty et al. 2012; Bettencourt 2014; Bibri 2019c, 2020a). Besides, "we are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of modern cities, coupled with the … integration and coordination of their systems and domains. As a result, vast troves of data are generated, analyzed, harnessed, and exploited to control, manage, and regulate urban life" (Bibri 2019b, p. 1).

The wave of the datafication of cities, as mainly enabled by the IoT technology, is giving rise to a new phenomenon–known as the data–driven city. The form of data–driven urbanism has become the key mode of production for both smart cities (Kitchin 2015, 2016) and sustainable smart cities (Bibri 2019a, 2019c). This has resulted from thinking about urbanization and sustainability and their relationships in a data–analytic fashion for the purpose of enhancing and applying knowledge–driven, fact–based, strategic decisions pertaining to various urban systems and domains (Bibri and Krogstie 2018). Unsurprisingly, there has recently been a conscious push for smart cities across the globe to be smarter and thus more sustainable by developing and implementing data–driven solutions to enhance and optimize their operations, functions, services, designs, strategies, and policies in the hopes of achieving the required level of sustainability and improving the living standards of citizens.

While smart cities have played a key role in transforming different areas of human life, they involve deficiencies, inconsistencies, and misunderstandings as to incorporating the objectives of sustainable development in their strategies (e.g., Bibri and Krogstie 2017a; Höjer and Wangel 2015; Kramers et al. 2014; Marsal-Llacuna 2016). Many of the emerging smart solutions are not aligned with sustainability goals in the context of smart cities (Ahvenniemi et al. 2017). There is a weak connection between smart targets and sustainability goals (Bifulco et al. 2016), despite the proven role of advanced ICT, especially big data analytics and its applications, in supporting smart cities in moving towards sustainability (e.g., Al Nuaimi et al. 2015; Angelidou et al. 2017; Batty et al. 2012; Bibri 2018a, 2020a; Bettencourt 2014). In fact, while the research on big data and the IoT technologies has recently been active in the area of smart cities, the bulk of work tends to deal largely with economic growth, service efficiency, and governance (e.g., Ahmed et al. 2017; Kitchin 2014, 2015, 2016; Hashem et al. 2016; Rathore et al. 2018). This area of research overlooks or barely explores the untapped potential of data-driven solutions for advancing sustainability. These gaps have been identified as

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part of a thorough literature review conducted by Bibri (2019c). And this study attempts to explore them by investigating the role of big data technologies and their applications in advancing smart cities in terms of sustainability from a practical perspective under what is labelled "data-driven sustainable smart cities."

This paper investigates how the emerging data-driven smart city is being practiced and justified in terms of the development and implementation of its innovative applied solutions for sustainability. As with all approaches to smart urbanism, data-driven cities have commonalities and differences depending on the challenges they face and thus the innovative solutions they prioritize. While all smart cities are set to face the same challenges of sustainability in the face of the escalating scale and rate of urbanization, they tend to differ in terms of the strategies they pursue to overcome them. City governments do not have a unified agenda of sustainable development, and data-driven decisions are unique to each city. While big data are seen as the answer, each city sets its own questions and determines the ways to address them. The motivation for this study is to identify the core dimensions of the emerging data-driven smart city and to use the outcome to inform the backcasting study that is being conducted to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future in terms of its technological components.

The remainder of this paper is structured as follows. Section 2 provides the key conceptual and theoretical constructs that make up this study. Section 3 details and justifies the research methodology adopted in this study. Section 4 provides an overview of the literature review previously conducted in relation to this study. Section 5 presents the results, which are, in Section 6, discussed and interpreted in perspective of previous studies. Finally, this paper concludes, in Section 7, by drawing the main findings, providing some reflections, and suggesting some avenues for future research.

Conceptual and theoretical background

The data–Driven City as an emerging paradigm of smart urbanism

The data-driven city is one of the recent faces and future forms of smart cities. As such, it represents an emerging paradigm of smart urbanism. Indeed, it is too often associated with 'smarterness' under what is labeled 'data-driven smart cities', since big data technology is seen as an advanced area of ICT, which is an enabler of all approaches to smart cities (e.g., ambient city, sentient city, ubiquitous city, real-time city, etc.) as an umbrella term. There is no definite definition or a single conceptual unit of a data-driven city, nor is there an agreed industry description thereof. Therefore, multiple definitions have been suggested, with each tending to offer a particular view of the concept based on the context of big data uses and applications, thereby serving as a constituting or complementary aspect of a rather still evolving concept.

Broadly, the phenomenon of the data-driven city has materialized as a result of the emergence of big data science and analytics and the adoption of the underlying technologies in scholarly research and social practice, the explosive growth of urban data, and the transformation of urban landscape in the light of urbanization. These developments can be used in a range of proposals for a conceptual framework for a data-driven city. As an example, Nikitin et al. (2016) use, in their research framework, a notion which embraces the basic elements used in the management of the data-driven

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city: data, processing technologies, and government agencies. The authors accordingly describe the data-driven city as a city that is characterized by the ability of agencies of city management to use technologies for handling the data for the adoption of solutions for enhancing living standards thanks to the development of social, economic and ecological areas of urban environment.

One of the key foci of the data-driven city is sustainable development. In this respect, Bibri (2020a) describes a data–driven smart sustainable city as a city that is increasingly composed of and monitored by ICT of ubiquitous computing and thus has the ability of using advanced technologies and solutions (i.e., horizontal information systems, operations centers, service agencies, research centers, innovation and living labs, and strategic planning and policy offices) for generating, storing, processing, analyzing, and harnessing urban data for enhanced decision-making and deep insights pertaining to sustainability, efficiency, resilience, and the quality of life.

Datafication

The data-driven city is a city that implements datafication for enhancing and optimizing its operations, functions, services, strategies, and policies. Broadly, datafication refers to the collective tools, processes, methods, techniques, and technologies used to transform a city to a data–driven enterprise. The intensification of datafication is manifested in the radical expansion in the volume, range, variety, and granularity of the data generated about urban environments and citizens (Bibri 2019b, 2020a; Crawford and Schultz 2014; Kitchin 2014, 2016; Strandberg 2014), with the aim to quantify the different aspects of urbanity in the modern city.

Cities today are dependent upon their data to operate properly—and even to function at all with regard to many domains of urban life. A city that implements datafication is said to be datafied. To datafy a city is to put it in a quantified format so that it can be structured, harnessed, and analyzed. Cities are currently taking any possible quantifiable metric and squeezing value out of it by enhancing decision–making pertaining to a wide variety of practical uses in relation to many urban systems and domains. In a modern data–oriented urban landscape, a city's performance is measured, assessed, and enhanced based on the ability of having control over the storage, management, processing, and analysis of the urban data, as well as on the knowledge extracted from these data in the form of applied urban intelligence. Tackling the challenges of sustainability and mitigating the negative effects of urbanization are among the key concerns of the datafication of the modern city (Bibri 2019a, 2020a).

The internet of things (IoT)

The IoT has become a key component of the ICT infrastructure of smart cities due to its great potential to advance sustainability. According to Giusto et al. (2010), the IoT is a "communication paradigm which visualizes a near future, in which physical objects are equipped with micro–controllers, transceivers for digital communication and fitting protocol stacks that will make these objects able to communicate with each other and with the users." Bibri (2020a) defines the IoT as the interconnection of uniquely identifiable embedded devices and smart objects connected to humans, embedded in their environments, and spread along the trajectories they follow using the Internet Protocol

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version 6 (IPv6), embedded systems, intelligent entities, and communication and sensing–actuation capabilities. The IoT is evolving into more and more sophisticated network of sensors and physical objects involving all kinds of everyday objects, including individuals, roads, railways, bridges, street lighting, buildings, water systems, energy systems, distribution networks, vehicles, appliances, machines, and air. In short, the connectivity achieved by the IoT encompasses people, machines, tools, and places. Reports show that the number of Internet–connected devices is expected to increase more than twofold from 22.9 billion in 2016 to 50 billion by 2020 (Ahmed et al. 2017).

As one of the prevalent ICT visions of pervasive computing, the IoT is associated with big data analytics. A great part of the unfolding deluge of urban data is due to the IoT as a form of ubiquitous computing. To gain further insights into this relationship, the interested reader might want to read a recent survey carried out by Qin et al.'s (2016) and Bibri (2018b). However, the IoT entails complex sensor infrastructure and network, and thus requires novel techniques, tools, processes, and models to handle the volume, variety, and velocity of the data generated to enable new services and applications.

The IoT is viewed as part of the Internet of the future, which is expected to be dramatically different from what has hitherto been experienced in terms of the use of the Internet as we know today. The use of the IoT is intended to achieve different intelligent functions from 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. In short, the objective of the IoT is to enable communications with and among smart objects as well as with people and their environment, without any human intervention. Zanella et al. (2014) state that "the intention of the IoT is to make the Internet even more engaging and omnipresent by allowing easy entrance and communication with a large variety of devices so that it can support the development of a number of applications which make use of the possibly gigantic bulk and diversity of the data produced by objects to present new services to citizens, companies and public administrations." This involves the value that is to be extracted from the deluge of urban data for enhanced decision–making and deep insights associated with a wide variety of practical uses and applications in relation to sustainability. This is associated with smart cities (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Hashem et al. 2016), data-driven cities (Nikitin et al. 2016), and sustainable smart cities (Bibri 2019c, 2020a). The IoT–based infrastructures will allow different classes of cities to devise solutions for solving different problems in a more efficient, effective, and responsible way. The upcoming data avalanche is the primary fuel of this new age where powerful computational processes use this fuel to create more sustainable, efficient, resilient, livable, and equitable cities.

Sustainable smart urbanism: a data-driven approach to sustainable urban development

Rooted in the study of the relationship between urban planning and sustainable development in a rapidly urbanizing world, sustainable urbanism is concerned with the study of cities and the practices to build them that focus on promoting their long term resilience and viability by reducing material use, lowering energy consumption, mitigating

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pollution, and minimizing waste, as well as improving social equity, the quality of life, and well-being.

The sustainable smart city as a holistic paradigm of urbanism represents an approach to sustainable urban development, a strategic process to achieve the long–term goals of urban sustainability—with support of advanced technologies and their novel applications. Accordingly, achieving the status of such city epitomizes an instance of urban sustainability. This notion refers to a desired (normative) state in which a city strives to retain a balance of the socio–ecological systems through adopting and executing sustainable development strategies as a desired (normative) trajectory. This balance entails improving and advancing the environmental, economic, social, and physical systems of the city in line with the vision of sustainability over the long run—given their interdependence, synergy, and equal importance. This strategic goal requires fostering linkages between scientific research, technological innovations, institutional frameworks, policy formulations, planning practices, and development strategies in relevance to sustainability.

Furthermore, the sustainable smart city relies on constellations of instruments across many scales that are connected through multiple networks augmented with intelligence, which provide and coordinate continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the environmental, economic, social, and physical forms of the city. The evolving research and practice in the field of sustainable smart urbanism tends to focus on harnessing and exploiting the ever–increasing deluge of the data that flood from urban systems and domains by leveraging the value extracted from this deluge through analytics in advancing sustainability. In this respect, sustainable smart urbanism entails developing urban intelligence functions as an advanced form of decision support, which represent new conceptions of how the sustainable smart city functions and utilizes and integrates complexity science, urban science, and data science in fashioning powerful new forms of urban simulations models and optimization and prediction methods. These can generate urban structures and forms that improve sustainability, efficiency, resilience, and the quality of life.

The data–driven solutions are of paramount importance to sustainable smart urbanism as a set of processes and practices. One key aspeect of this is the use of urban data as the evidence base for formulating urban policies, plans, strategies, and programs, as well as for tracking their effectiveness and modelling and simulating future urban development projects. In addition, the operation and organization of urban systems and the coordination of urban domains require not only the use of complex interdisciplinary knowledge, but also the application of sophisticated approaches and powerful computational analytics (e.g., Batty et al. 2012; Bibri 2019a, 2020a; Bibri and Krogstie 2017b, Bibri and Krogstie 2018; Bibri et al. 2020a; Bettencourt 2014). In their comprehensive survey on emerging data–driven smart cities, Nikitin et al. (2016) point out that modern cities employ the latest technologies in city management to support sustainable development given rapid urban growth, increasing urban domains, and more complex infrastructure.

Literature review

This study is based on a thorough literature review conducted by Bibri (2019c)—an article entitled "On the Sustainability of Smart and Smarter Cities in the Era of Big Data:

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An Interdisciplinary and Transdisciplinary Literature Review." This literature review provides a theoretical foundation for this study in terms of what is already known, produces a rationale for this study as to its contribution of something new to the body of knowledge, helps understand where excess research exists and what kind of questions are left unanswered, substantiates the presence of research problem in regard to what is needed to be known, and frames research methodology, approach, and aim. In a nutshell, what is accomplished by this literature review is knowing the current status of the body of knowledge in the research field of smart urbanism, which is an essential first step for this study. The main aspect of this status pertains to the gaps identified and how to explore them by investigating the role of big data technologies and their applications in advancing smart cities in terms of sustainability from a practical perspective under what is labelled "data-driven sustainable smart cities".

To find out about what is known about the topic on focus, Bibri (2019c) provides a comprehensive, state–of–the–art review on the sustainability and unsustainability of smart cities in relation to big data technology, analytics, and application in terms of the underlying foundations and assumptions, research problems and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. An exhaustive, by its nature, a methodological approach is adopted for carrying out this interdisciplinary literature review, thereby delivering a relatively complete census of the relevant existing work on the topic. Such approach entails search strategy and scholarly sources, inclusion and exclusion criteria, purposes, and organisational approaches. As regards the findings, this study reveals that tremendous opportunities are available for utilizing big data technologies and their applications in smart cities of the future. This is to enhance and optimize urban operations, functions, services, designs, strategies, and policies in line with the goals of sustainability, as well as to find answers to challenging analytical questions and to transform the knowledge of smart urbanism. However, just as there are immense opportunities ahead to embrace and exploit, there are enormous challenges and open issues ahead to address and overcome in order to achieve a successful implementation of big data technologies and their applications in smart cities of the future. These findings serve to aid strategic city stakeholders in understanding what they can do more to advance sustainability based on data-driven technological solutions under what is labeled 'data–driven sustainable smart cities,' and to give policymakers an opportunity to identify areas for further improvement while leveraging areas of strength with regard to the emerging and future form of urbanism.

Case study methodology

Case study as an integral part of a Backcasting-based futures study

This case study is an integral part of an extensive futures study that is being conducted to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future using backcasting as a scholarly and planning approach (Bibri and Krogstie 2019a, 2019b). Specifically, it is associated with the empirical phase of the backcasting-based futures study. The term "backcasting" was coined by Robinson (1982), and the approach was originally developed in the 1970s as an alternative to traditional energy planning and employed as a novel analytical tool for energy planning

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using normative scenarios. Backcasting scenarios are used to explore future uncertainties encountered in society, create opportunities, build capabilities to take strategic steps, guide policy actions, and enhance decision–making processes (Bibri and Krogstie 2019a, 2019b). They allow for new options to be considered reasonable, thereby widening the perception of what could be feasible and realistic in the long-term (e.g., Dreborg 1996; Höjer and Mattsson 2000). The fundamental question of backcasting-based futures studies is: "If we want to attain a certain goal, what strategic actions must be taken to get there?" Accordingly, backcasting starts with defining a desirable future and then works backwards to identify the strategic steps needed to build feasible and logical pathways between states of the future and the present. Developing pathways from this perspective allows to imagine the impacts of alternative scenarios, which are commonly used as a tool for strategic planning, especially in relation to sustainability. Having a strongly normative nature, backcasting is especially well equipped to be applied to sustainability issues (Bibri 2018c; Dreborg 1996; Holmberg 1998; Quist 2007; Robert et al. 2002). Many authors have justified the need for a normative scenario approach by referring to the emerging disruptions in societal development (Dreborg 1996; Quist and Vergragt 2006), e.g., technological breakthroughs, data-intensive scientific discovery, and sustainable development.

Case study Research

Case study research has long been of prominence in many disciplinary and interdisciplinary fields. As a research methodology, case study is well established in different scientific and technological fields. Creswell et al. (2007, p. 245) describe case study methodology as "a type of design in qualitative research, an object of study, and a product of the inquiry." The authors conclude with a definition that collates the hallmarks of key approaches and that represents the core features of a case study: "a qualitative approach in which the investigator explores a bounded system (a case) or multiple bounded systems (cases) over time through detailed, in–depth data collection involving multiple sources of information and reports a case description and case–based themes" (Creswell et al. 2007, p. 245).

Case study design category

According to their design, case studies can be divided into several categories, including descriptive, explanatory, exploratory, illustrative, cumulative, and critical instance, each of which is custom selected for use depending on the objectives of the researcher or the purpose in evaluation. Case study research can be used to study a range of topics using different approaches for different purposes (Simons 2009; Stake 2006; Stewart 2014; Yin 2017). With that in mind, this case study uses a descriptive design, an approach which is focused and detailed, and in which questions and propositions about the phenomenon of the data-driven smart city are scrutinized and articulated at the outset. The articulation of what is already known about this phenomenon is referred to as a descriptive theory, which in this context pertains to smart urbanism. Therefore, the main goal of this descriptive case study is to assess the selected cases in detail and in depth based on that articulation. This research design intends to describe the phenomenon in question in its real–world context, to draw on Yin (2014, 2017). It is

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worth pointing out that the internal validty in this research design, the approximate truth about inferences regarding cause-effect in relation to this phenomenon is not relevant as in most descriptive studies. It is rather relevant in studies that attempt to establish a causal relationship such as explanatory case studies. Indeed, descriptive research is used to describe some characterisitics of certain phenomena, and does not address questions about why and when these characteristics occur - no causal relationship.

Descriptive case study relevance and approach

Descriptive research here involves the description, analysis, and interpretation of the present nature, composition, and processes of data-driven smart cities, where the focus is on the prevailing conditions, or how these cities behave in terms of what has been realized and the ongoing implementation of plans based on the corresponding practices, strategies, and solutions. Moreover, as an urban event based on two instances, the data-driven smart city involves a set of indicators of an integrated city system in operation that requires an analysis to allow obtaining a broad and detailed form of knowledge about such system. To achieve this, we adopted an approach that consists of the following steps:

- Using a narrative framework that focuses on the data-driven smart city as a real–world problem and provides essential facts about it, including relevant background information
- Introducing the reader to key concepts, technologies, practices, and strategies relevant to the problem under investigation.
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes.
- Offering analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

One of the essential requisites for employing case study stems from one's motivation to illuminate a complex phenomenon (Merriam 2009; Stake 2006; Yin 2017). Accordingly, the outcome of this descriptive case study should serve as an input to Step 5 (specifying and merging the components of the socio–technical system to be developed) and Step 6 (performing backcasting backward–looking analysis) of the backcasting study, By carefully studying any unit of a certain universe, we are in terms of knowing some general aspects of it, at least a perspective that guides and informs subsequent research (Wieviorka 1992). In other words, descriptive case studies often represent the first scholarly toe in the water in new areas of inquiry.

Descriptive case study as a basis of Backcasting

One important use of the case study approach in research is planning, which in turn is at the core of the backcasting approach to futures studies. However, the purpose of analyzing and evaluating the two cases considered here together with the other four cases—two compact cities (Bibri et al. 2020b) and two eco–cities (Bibri and Krogstie 2020)—is to provide a foundation for backcasting the future phenomenon of the data-driven smart

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sustainable city. In this case, it is necessary first and foremost to define which characteristics of the future state of this phenomenon are 'interesting' and should be included in the backcasting (see Bibri and Krogstie 2019a, 2019b for Step 1, 2, and 3 of the backcasting study). Evidently, recent data in this regard are of primary importance as a basis for the backcasting. Other material needed to make a backcasting depends on how strong a 'theoretical and disciplinary framework' we have about the expected data-driven smart sustainable city of the future and its internal relationships (see Bibri 2018a, 2019a, 2020a for further details). Commonly, quite a strong basis for backcasting is available when there is such a framework which underpins and explains the phenomenon in question in terms of its foundation and justification, as well as its associated outcomes as a new and future paradigm of urbanism. All in all, the results of all the case studies carried out are intended to guide and inform the backcasting study in question as an overarching scholarly endeavor.

Selection criteria, unit of analysis, and data collection and analysis methods

The selection of all of the cases studied was done in line with the overall aim of the futures study being carried out. The primary purpose of investigating the cases of Barcelona and London is to identify the set of the data-driven solutions that are needed to develop the proposed model for data-driven smart sustainable cities of the future in terms of its technological components. The urban components of this model have already been identified through two separate case studies: compact city strategies and eco-city strategies, as mentioned earlier.

Selecting Barcelona and London amongst all the top cities leading the 'smart city' ranking (e.g., Eden Strategy Institute 2018) and the 'data-driven' city ranking (Nikitin et al. 2016) in the world is justified by three key reasons. First, the focus of the backcasting study, and thus this paper, is on the European Cities of which London and Barcelona are the leading data-driven smart cities. Second, both cities are widely recognized and mostly reputed for using data-driven technology solutions in their operational functioning, management, and planning, and what this entails in terms of competences, infrastructure, and data sources (e.g., Bibri 2020a; Batty 2013; Eden Strategy Institute 2018; Kitchin 2014, 2016; Nikitin et al. 2016; Sinaeepourfard et al. 2016). Third, they are increasingly seen as the leading European cities that are taking the initiative to use and apply big data technology to advance sustainability—thereby evolving into data-driven sustainable smart cities (Bibri 2020a). The local governments of London and Barcelona have established a number of projects and implemented several planning measures for modernizing their ICT infrastructure and strengthening their readiness to integrate data-driven solutions and approaches into urban processes and practices.

In view of the above, the two cities demonstrate exemplary practical initiatives as regards the integration of data-driven solutions and sustainable development strategies. As such, they may be seen as successful examples of the emerging paradigm of smart urbanism, as well as critical cases in sustainable development within the technologically advanced nations. All in all, the selection criteria secured cases where advancements in big data technologies and their novel applications for sustainability, coupled with future visions in this regard, are present. This in turn is at the core of the backcasting study in respect of the integrated model under development.

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The focus of the backcasting study constitutes the basis for determining the unit of analysis concerning the cases in question. The object of study in this paper, the entity that frames what is being analyzed, is the applied solutions of the emerging data-driven smart cities and to what extent they contribute to and produce the benefits of sustainability. This is essential to focalizing, framing, and managing data collection and analysis.

To identify and analyze the relevant dimensions of the data-driven smart city with respect to sustainability, a thematic analysis approach was designed and employed. Thematic analysis is particularly (albeit not exclusively) associated with the analysis of textual material (in this context, plans, programs, project descriptions, policy documents, and secondary data sources). Generally, it emphasizes identifying, analyzing, interpreting, and reporting themes, i.e., important patterns of meaning within qualitative data that can be used to address the problem under investigation. Braun and Clarke (2006) suggest that thematic analysis is flexible in terms of theoretical and research design given that it is not dependent on any particular theory or epistemology: multiple theories can be applied to this process across a variety of epistemologies.

Thematic analysis is an umbrella term for a variety of different approaches, which are divergent in regard to procedures. We adopted an inductive approach to thematic analysis, which allows the data to determine the set of themes that are to be identified in line with the aim of this study. That is to say, we developed our own framework based on what we find as themes (inductive) by discovering patterns, themes, and concepts in the data collected.

The main steps of the analytical approach are as follows:

1. Review of city data (i.e., plans, programs, project descriptions, policy documents, and other secondary data sources) and the scientific literature that is related to the role of data-driven technologies in advancing sustainability. The outcomes of this process are numerous themes that are associated with the emerging data-driven approach to smart urbanism. It is important to have a comprehensive understanding of the content of the documents and scientific literature and to be familiarised with all aspects of the data. This step provides the foundation for the subsequent analysis.
2. Pattern recognition (searching for themes) entails the ability to see patterns in seemingly random information. The aim is to note major patterns within the result of the first step. This second step looks for similarities within the sample and codes the results by concepts and themes. Coding involves identifying passages of text that are linked by a common theme, allowing to index the text into categories and thus establish a framework of thematic ideas about it. In this step, the preliminary codes identified are the features of the data that appear interesting and meaningful, and the relevant data extracts are sorted according to overarching themes. It is important to allude to the relationship between codes and themes.
3. Reviewing themes is about combining, separating, refining, or discarding initial themes in line with the aim of this study and thus the backcasting study. Data within themes should cohere together meaningfully and be clear and identifiable in terms of the distinction between them. A thematic 'map' is generated from this step.

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4. Producing the report involves transforming the analysis into an interpretable piece of writing by using vivid and compelling data extracts that relate to the themes, research aim, and literature associated with this study. The report must go beyond a mere description of the themes and portray an analysis supported with empirical evidence that addresses the research problem.

All in all, the descriptive case study approach was applied here as a framework to collect and analyze data from different documents related to the selected cases. A thematic analytical approach was employed to deal with the “case-based themes” (Creswell et al. 2007). The backcasting methodology is adopted in the overarching futures study to combine the results of this case study with those of the other aforementioned case studies in order to develop a new paradigm of urbanism.

Results

On the ranking and score of London and Barcelona

Technologies and readiness

In the early 2010s, London and Barcelona were the first European cities to implement data-driven smart technologies to improve their services. They invested heavily in their ICT infrastructure, including an extensive IoT sensor network collecting data about transport, energy, environment, security, healthcare, and so on. Implemented in London and Barcelona is a broad range of applied technological solutions based on the analysis of the data generated by a variety of sources, with the aim to improve the quality of life of citizens. The focus of the Smart London Plan is on using the creative power of big data technologies to serve citizens and improve their lives (London City 2018). In 2015, Barcelona took the initiative of the smart city in a new direction by setting a goal of democratizing its ICT infrastructure, with a vision to develop it by and for the people (Bibri 2020a). That is, to serve people as technology users—instead of a technology push agenda.

In their comparative study of the practice of urban data-based management using statistical analysis and expert analysis, Nikitin et al. (2016) analyze the data-based technologies applied in the 28 megalopolises of the world to compare cities by the number of references in a variety of types of sources, and identify London and Barcelona among the first four leading cities. The results of this analysis are illustrated in Fig. 1.

Table 1 briefly describes the key indicators associated with the comparative analysis of the two cities in relevance to this study, namely readiness and technologies. These indicators are the key foci of this study.

Smart City government score

In ranking the top 50 smart city governments in the world, Eden Strategy Institute (2018) classifies the governments of London and Barcelona as the leading in Europe, and calculates a total score for each based on different aspects related to the smart city initiative (Fig. 2).

Data-driven technologies and their applications for City systems and domains

Smart cities are increasingly embracing big data technologies and their novel applications, especially those related to and enabled by the IoT. This is due to the tremendous, yet

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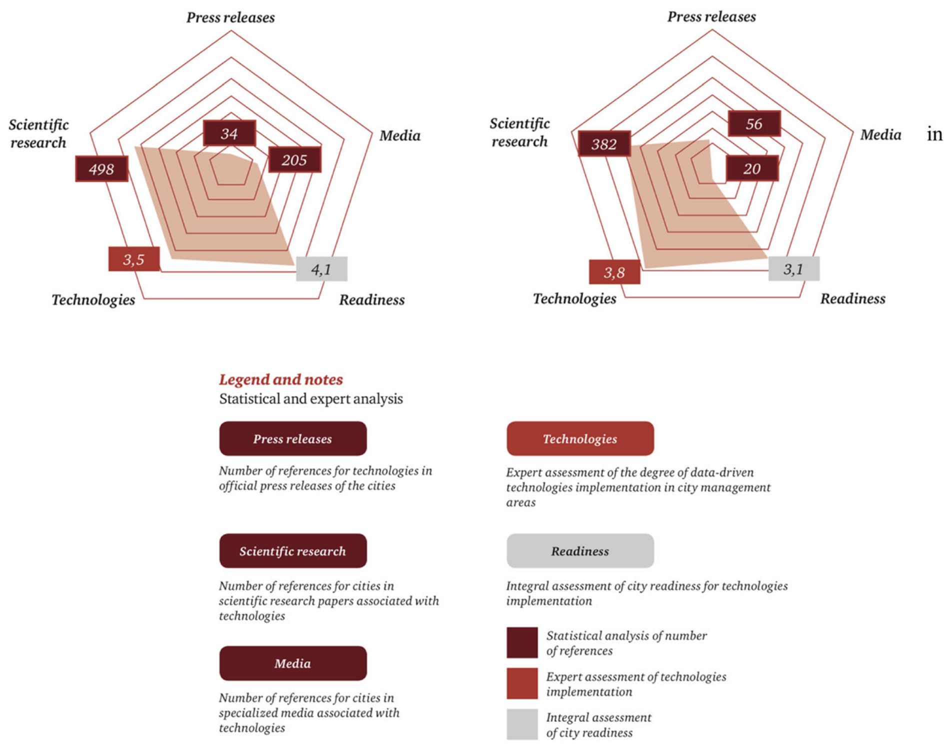

Fig. 1 A comparative analysis of London and Barcelona

untapped, potential of big data analytics for adding a whole new dimension to sustainability in an increasingly urbanized world. There is a huge range of data-driven applications that are compatible with the goals of sustainable development. As with all the emerging smart cities focusing on sustainability, London and Barcelona may differ on the level of the development of data-driven technologies and that of their implementation in city systems and domains. One of the recent studies that have addressed these issues and aspects with respect to these cities is the one conducted by Nikitin et al. (2016). The results reported in this regard are presented in Table 2.

While the two cities have a high level of the development of data-driven technologies, they slightly differ in the level of the implementation of these technologies in different urban systems and domains. This indicates differences in the agenda of city development, including in relation to sustainability. The effectiveness of individual initiatives as related to different domains (e.g., transport, traffic lights, energy, environment, etc.) may also vary significantly between London and Barcelona with respect to the extent to

Table 1 Indicators of data-driven technology implementation and its readiness

Cities	Indicators of data-driven implementation of technologies and its readiness
London	The municipal systems are highly ready for the introduction of technologies. London stands apart with a decentralised development model. The agenda shows the impact of creative industries on settlement patterns, distribution of activities within the city and geographical location-related services.
Barcelona	Barcelona stands out with its high level of technology development and is highly ready to further implementation. Barcelona is extensively implementing data-based solutions. "Modelling", "efficiency" and "optimisation" are used in the texts.

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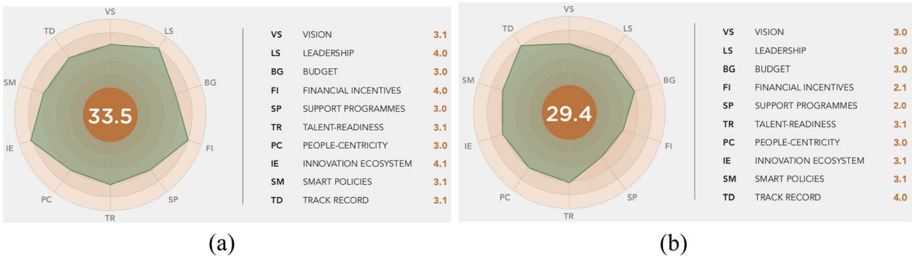

Fig. 2 Smart City Government Score of London (**a**) and Barcelona (**b**). Source: Eden Strategy Institute (2018)

which the planned objectives can be achieved. Regardless, scholars agree on the high value of the implementation of data-based decisions in smart urbanism with respect to sustainability (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri 2018a, b, 2019a, 2019b, c).

London and Barcelona are among the world leaders in the implementation of the data-based technologies and decisions (Nikitin et al. 2016). London is one of the leaders in advanced technologies and digitization (Pozdniakova 2018). Both cities have the highest level of technology adoption in Europe as observed in various systems and domains, with a slight difference in a few of them. The greatest variety of the data-based decisions is found in the systems and domains of transport and security in both cities (Nikitin et al. 2016). The extensive use of such decisions (e.g., traffic control, public transport planning, etc.) is based on the IoT (e.g., geolocation and Radio Frequency Identification (RFID) and Near Field Communication (NFC) technologies), which allows to automate or support a variety of decisions.

Transport, traffic, and mobility

Transport and traffic management is generally the most popular area of using data-driven solutions within smart cities and sustainable smart cities (e.g., Aguilera et al. 2013; Batty 2013; Bibri 2018b, 2019b; Hashem et al. 2016; Shang et al. 2014). Both London and Barcelona apply the data-driven technology for transport and traffic management. With respect to London, the application of such technology pertains to the management of transport services on the basis of the data received by the situation center, as well as the automatic control of traffic signals on the basis of the data collected on traffic congestion using sensors embedded in the traffic lights. As regards Barcelona, the application entails monitoring the movements of public transport by means of Global Positioning System (GPS) sensors, as well as the smart traffic light system for the automatic provision of priority to public transport and other types of transport such as emergency services. Further development in the domain of transport technology in London and Barcelona is going in the direction of the automation of management in real time (i.e., smart traffic lights, smart parking, automatic traffic alerts, etc.). Implemented in Barcelona is several technological innovations that improve city operations

Table 2 Assessment degree of technology implementation based on a scale between 2.5 and 5.0

	Technology implementation	Transport	Utilities	Safety	Environment	Healthcare	Others
London	3.5	4.0	3.5	3.0	3.0	3.0	4.5
Barcelona	3.8	4.0	4.5	3.0	5.0	3.0	3.5

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in regard to transport. Among the solutions applied in this regard are (Bibri 2020a; Ilhan and Fietkiewicz 2017; Eden Strategy Institute 2018):

Orthogonal bus system: the city's bus network is based on an orthogonal grid scheme, which promotes intermodality, strategically placing bus stops to allow connection between bus lines as well as trams, metro trains, bicycles, etc. Because buses are laid out on a grid, every bus line intersects with multiple other bus lines, so citizens can reach any point in the city without changing buses more than once. Hybrid buses are used to decrease emissions, and solar-powered signs show times of arrival at bus stops. The bus network is based on data analysis of the most common traffic flows in Barcelona, utilizing primarily vertical, horizontal and diagonal routes with a number of interchanges. Integration of multiple smart technologies can be seen through the implementation of smart traffic lights as buses run on routes designed to optimize the number of green lights.

Bicing—a bicycle sharing system: the system offers 6000 bicycles which can be borrowed for short trips across the city. Bicycle pickup stations are placed near public transportation and parking areas, making it convenient for citizens to pick up or drop off bicycles. Citizens pay an annual fee and check for bicycle availability using the Bicing app, which has more than 120,000 users.

Smart parking system: This solution enables to reduce traffic by helping drivers find parking places, decreases congestion, and makes the streets safer. Wireless sensors are implemented underneath the roads and installed on the streets to guide vehicle drivers to available parking spots, enabling real-time query via a smartphone app. This app also enables paying for parking and provides parking data for use by other smart city systems. The smart parking system had operational challenges because the original magnetic sensors were set off by passing trains and falsely reported parking slots as occupied, and as a result, the project was deprioritized.

In addition, Barcelona uses smart traffic lights for optimizing the traffic in the real time mode. A smart system manages the traffic lights by processing the information received from the traffic magnetometer sensors with wireless capabilities This eliminates disruptions to the traffic flow, among others.

Street lighting is being expanded beyond its original use, e.g., illuminating the streets, making citizens feel safer, monitoring energy consumption, saving costs, and so on. It has been argued that street lights and city-wide lighting infrastructure could be the backbone for building sustainable smart cities of the future by transforming urban spaces in such a way that they can collect data that can make urban living more environmentally sustainable and enhance citizens' lives thanks to the IoT and related sensor networking and communication capabilities. In this regard, the lighting infrastructure could facilitate and incorporate a number of applications related to traffic, mobility, pollution, air quality, parking, public Wi-Fi connectivity, and so forth. Speaking at the Smart To Future Cities conference in London, Ms. Kressler said: "Street lighting is an ideal backbone, and the most interesting pathway, to employing the IoT technologies in cities. Technology is just an enabler–a smart city will only be successful if it shows real benefits to its citizens and its civic leaders" Forsdick (2019a). She moreover states that 40% of the local authority's energy budget is spent on street lighting, while smart street light controls and the IoT connectivity can create energy savings of 70% to 80%. What makes the lighting infrastructure an effective applied technological solution for

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sustainability is its pervasiveness, connection to power supply system, and high visual impact. As such, it enables smart cities to achieve their sustainability ambitions at a lower cost, particularly in connection with environmental sustainability.

With respect to Barcelona, smart lighting entails sensor-controlled light emitting diode (LED) lights for pedestrian and bicycle paths, self-controlled-LED street lights with preset lighting schedules, and remote-controlled lights. Accordingly, the street lights are powered by energy-efficient LED technology and use sensors to detect when lights are required (e.g., turned on when bystanders are present), saving energy and reducing the heat generated by the old lamps. Moreover, they include sensors that detect changes in temperature and pollution levels and are used as Wi-Fi transmitters. This implies that more advanced applications are being integrated into the lighting infrastructure. One of these applications is where an emergency is reported in Barcelona, the approximate route of the emergency vehicle is entered into the traffic light system, setting all the lights to green as the vehicle approaches through a mix of GPS and traffic management software, allowing emergency services to reach the incident without delay. Much of these data is managed by the Sentilo Platform (Bibri 2020a). On the whole, the benefits of the smart lighting solution in Barcelona lie in optimizing the efficiency of the public-lighting installations as well as increasing the level of the security of the streets through quality lighting thanks to the combination of LED lighting and control systems, including light on demand systems and street lighting remote management system.

In addition, according to the Smart London Plan, the city plans to demonstrate how technology can reduce traffic collision and trial new technologies that can reduce the risk of collisions with cyclists and other vulnerable road users (London City 2018). Moreover, at the Smart to Future Cities Conference in London, which was held in April 2019, Smart London Strategy Officer Dr. Stephen Lorimer claims: “Londoners are the first to see the economic, social, and environmental sustainability policies introduced under the same banner through the congestion charge and Ultra Low Emission Zone (ULEZ), and it is the first time residents have tangibly seen that cars are having an impact across all three pillars of sustainability in cities” (Forsdick 2019a).

In terms of urban mobility, a variety of apps are being used by the residents of London and Barcelona to remain updated and connected and to utilize transport and traffic services. Government announces funding for a world-leading Smart Mobility Living Lab in London (TRL 2017). Transport for London (TfL) analyzes the data collected from Oyster cards on public transport events corresponding to entries, exits, transfers, and so on to examine journey patterns. TfL has very detailed data on buses and trains that give precise geo-positioning, times, and delays with respect to timetables, and that can be minded and visualized. A number of algorithms have, since the early 2010s, been developed for constructing multimodal trips associated with the data collected on public transport events. The unified TfL API brings together data across all the modes of transport into a single RESTful API, and provides access to the most highly requested real-time and status information across these modes in a single and consistent way (Nikitin et al. 2016).

In order to mine human mobility data, a number of various analytical methods for spatio-temporal data have been developed to create a variety of mobility apps. Among the mobility apps that are used in Barcelona are (Bibri 2020a):

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- TMB virtual: an app that uses mobile phone cameras to navigate citizens to the most relevant public transport stations
- Trànsit: a navigation app updated with real-time traffic conditions for drivers
- fassisApparkB: an app that helps direct drivers to an available parking spot

In London and Barcelona, the data are open and used by app developers as a unique source of real-time data on all the modes of transport for different practical purposes. Big data technologies are able to improve mobility on many levels, thereby increasing spatial and aspatial accessibilities to diverse opportunities. This enables the citizenry to improve the quality of their life. Big data sets concerning human mobility have become the fundamental ingredient for the new wave of urban analytics thanks to the widespread diffusion of wireless technologies, which allow for sensing and collecting massive repositories of spatio-temporal data. This research wave has increasingly attracted scientists from diverse disciplines given its importance in such domains as urban planning, transport planning, public health, economic forecasting, and sustainable mobility. With respect to the latter, for example, the sensors installed in bicycle lanes/cycle tracks and sidewalks/footpaths are able to monitor the number of cyclists and pedestrians to determine the most popular places in the city. Based on this information, the city government can identify priority areas for reconstruction/redevelopment and plan new or alternative routes for cyclists and pedestrians.

Urban infrastructure

Urban infrastructure management constitutes one of the key applications of the IoT and big data analytics in terms of monitoring, control, automation, and optimization. This involves the operations of roads, railway tracks, bridges, and tunnels (e.g., Gubbi et al. 2013). This relates to the events and changes associated with the structural conditions of urban infrastructure that can increase risk and cost and compromise safety and service quality. In this regard, the IoT devices can be used to improve incident management, enhance emergency response coordination and service quality, and reduce operational costs in all infrastructure related areas (Bibri 2018b).

As to the intelligent management of urban infrastructure and distributed network, such as water supply system, power supply system, waste management system, and lighting, a number of data-driven solutions are implemented in London and Barcelona due to the high importance of natural resources in regard to urban development strategies. As stated in the Smart London Plan (2018), the city aims to:

- Promote the use of smart grid technologies to better manage demand and supply of energy and water.
- Stimulate the use of data and technology to bring efficiencies and scale to the separation and utilization of waste as a resource.
- Investigate longer term infrastructure needs up to 2050—and using data and digital technology to meet those needs.

London strongly supports smarter heating, electricity, waste, and water networks that use resources efficiently and do more with less investments. Currently, the main areas of

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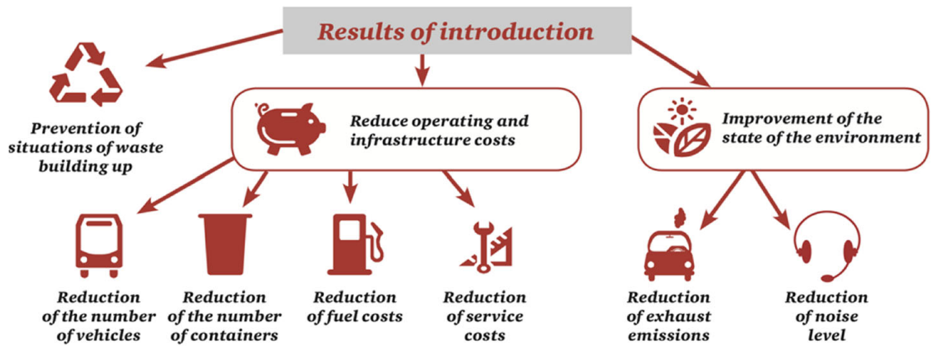

Fig. 3 Smart waste disposal system and its advatages in Barcelona. Source: Nikitin et al. (2016)

data measurement include the London Energy and Greenhouse Gas Inventory (energy consumption by homes, workplace, and transport) and the London Atmospheric Emissions Inventory (air pollution) (Pozdniakova 2018). Renewable energy systems are among the key smart solutions adopted by the City of Barcelona as to using sustainable energy sources to support its power grid system, such as solar panels distributed throughout the city. Considered to be the first regulations of their kind to be enacted in Europe, Barcelona has required the use of solar water heaters by households since 2006 as well as new large buildings to produce their own domestic hot water since 2000 (Bibri 2020a).

Smart waste disposal system, smart grid system, and smart energy management

Public services in London are in the area of responsibility of private companies, and consequently, the implementation of the data-driven solutions is often not systematic, as well as partial and not integrated with each other. The system of smart waste collection works well in Barcelona (see Fig. 3) where the special ultrasonic sensors mounted in the waste containers allow to define the degree of filling of the container, which enables to plan routes accordingly. That is to say, the smart bins detect the amount of waste they contain and the sanitation workers plan their collection routes in line with the data they receive from the bins. The resulting optimization of routes reduces harmful emissions by waste collecting machines. This system has a number of benefits in Barcelona, including reducing time spent on the collection of waste thanks to the optimization of movement of waste disposal means, which in turn allows decreasing costs for fuel consumed during the collection of waste (Nikitin et al. 2016). Moreover, some bins connect directly to the underground repositories; waste is sucked out by vacuum via underground pipes, which reduces the noise and congestion caused by garbage collection trucks. The energy generated from waste incineration is used for the city's heating system. More advanced uses of such energy are typically associated with smart eco-cities (see Bibri 2020b; Bibri and Krogstie 2020 for examples of practical cases). In addition, the application of the data-driven technology involves the integration of the information collected on projects into the development and redevelopment of urban infrastructure (Nikitin et al. 2016).

Furthermore, the implementation of the smart grid solutions in Barcelona and London entails a variety of operation and energy measures, including smart meters, smart appliances, and energy efficient resources. The smart grid system is cost-effective, secure, and sustainable. It integrates and coordinates energy production, consumption, supply, and

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facilities through enabling technologies, energy services, and active users. In Barcelona, the MONICA project develops a system capable of precisely establishing the status of the distribution grid in real time and at any given moment (Status Estimator), which provides real and immediate information about the impact on the quality and safety of the supply (Nikitin et al. 2016). This project deploys an entire network of medium and low voltage sensors that record measurements for all the electrical variables needed to be entered in the grid's new Status Estimator. This receives the collected data in real time via the deployed sensors and the existing smart meters diagnosing the different problems on the grid in order to prevent them or improve them, as applicable.

Among the data-driven smart applications pertaining to the smart grid system are:

- Supporting decision–making as regards the generation and supply of power in line with the actual demand of citizens and other consumers to optimize energy efficiency and thus achieve energy savings.
- Optimizing power distributed networks associated with energy demand and supply.
- Monitoring and analyzing energy consumption and Greenhouse Gases (GHG) emissions levels in real time across several spatial scales and over different temporal scales, as well as enhancing the performance and effectiveness of the power system.
- Managing distribution automation devices to improve the efficiency, reliability, and sustainability of power production and distribution.
- Avoiding potential power outages resulting from high demand on energy using dynamic pricing models for power usage by increasing charges during peak times to smooth out peaks and applying lower charges during normal times.
- Avoiding the expensive and carbon–intensive peaks in power grid using new ways of coordination with regard to the overall ensemble of users and consumers.

In addition, London and Barcelona use a number of data-driven smart applications for energy management (Bibri 2020a), which allow:

- Citizens to have access to live energy prices and adjust their use accordingly;
- The use of pricing plans in accordance with energy demand and supply models;
- Consumers to manage their usage based on what they actually need and afford;
- Self–optimizing and –controlling energy consumption through integrating sensing and actuation systems in relation to different kinds of appliances and devices for balancing power generation and usage;
- Users to remotely control their home appliances and devices based on the IoT by means of such advanced functions as scheduling, programming, and reacting to different contextual situations; and
- Energy systems to gather and act on near real–time data on power demand, consumption, and generation from end–user connections (information about producers and consumers' behavior).

Environment

The importance of the environment in modern cities can be justified by the fact that the latter occupy 2% of the world's surface, have more than 50% of the world

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population, consume 70% of global energy supply, and generate 75% of GHG emissions. It is clear that we can have a major positive impact on the environment by making cities more sustainable and greener thanks to the evolving digitally and computationally augmented urban environments that could change our relationship with nature by, for example, consuming less natural resources and protecting the environment.

In Barcelona, advanced technologies allow, thanks to the city's Wi-Fi-network, real-time tracking of the quality of the air in terms of the presence of various substances as well as applying preventive measures in a timely manner, in addition to monitoring the condition and composition of green space in urban areas (Nikitin et al. 2016). The real-time data collected about the air quality in the city are analyzed to determine the impact of the solutions that have been adopted in terms of improving environmental conditions, as well as to identify the areas where further actions are needed. Barcelona leads compared to London in the air quality by using a number of pollution prevention systems, including forecasting and modelling based on advanced machine learning techniques (Bibri 2020a). As to London, as stated in the Smart London Plan (London City 2016), it aims to have the best air quality of major cities of the world by 2020, which will require significant reduction in GHG emissions from the city's transport sectors, as well as to become a zero-carbon city by 2050. According to Nikitin et al. (2016), five «living laboratories» were created across London, where sensors measure a range of physical parameters, including air quality and human activity.

Furthermore, the analysis of the information on the noise levels in London is of a less common trend compared to Barcelona where local projects of this type are active today. Implemented in Barcelona is low-cost sensors that detect noise levels and pollution, aiding in identifying and countering violations of the city policy in this regard. The smart noise control solution used in Barcelona enables to optimize and centralize the collection, integration, processing, analysis, and dissemination of information by the noise sensors of different suppliers and sound level meters distributed throughout the city (Nikitin et al. 2016).

Civic security

The most common technology present in London and Barcelona are smart policy and applications for messages on incidents by residents. Also, the installation of closed-circuit television (CCTV) cameras is used in London to send signals to the emergency services in the event of unforeseen situations on the road. CCTV is moreover used to detect incidents and provide queuing alerts (London City 2018). In Barcelona, Citizens' Postbox is a mobile app that one can use to report incidents in real time occurring anywhere in the city (Nikitin et al. 2016). However, several European cities, including London and Barcelona, are launching platforms based on the IoT and multiple sensors to collect the data to build smart cities through lighting. Accordingly, most of the smart projects in Europe involving the use of incident detection technology in street lights are pilot. Such technology, partially implemented in Rotterdam, uses smart microphones with advanced pattern recognition to monitor the safety of citizens and quickly react to crimes in response to the requests made by the residents in their neighbourhood (Forsdick 2019b). This system is associated only with shots from firearms recognition system in London (Bibri 2020a).

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Citizen participation

Another technology implemented in London and Barcelona is crowdsourcing platforms, which is intended to address a number of issues related to different city areas. For example, citizens are being actively involved in solving urban problems to improve the efficiency of services and to enhance environmental performance in both cities (Bibri 2020a). The intent of London City (2018) is that technology innovators and entrepreneurs can help develop new approaches to service delivery. Barcelona launched Open Government portal to improve the transparency of the city management, where a number of initiatives have been realized with respect to engaging citizens in the solutions to the city issues (Nikitin et al. 2016).

The Smart London Plan (London City 2016) aims to put citizens at the center, with access to open data, leveraging the technology and creative talent of the city to enable it to better serve its citizens and to respond to their needs through increasing data sharing and analytics. London seeks to become a people-centric smart city (Misra 2018). It also aims is to explore ways of scaling up innovation, across administrative boundaries, to address the shared challenges of the city, such as waste collection and service delivery. Moreover, London City (2018) plans to establish a Smart London platform to allow citizens to feedback, rate, and shape the type of the experiences they want to have. In addition, London has established a number of digital literacy programs, and even investigated the reasons behind the digital exclusion of minorities and vulnerable groups (Eden Strategy Institute 2018). The London's new plan and Vision 2020 has digital inclusion focus as a core component of its strategy. The overall aim of the Government's Digital Inclusion Charter is to have everyone online, or with the aspiration to be online by 2020.

Barcelona actively involves citizens in policy decisions and in the development of services in the context of the smart city. With this commitment to citizen involvement, coupled with a strong technology platform, Barcelona is performing well in regard to leveraging smart technologies for the benefit of its citizens. Human capital is of utmost importance for future development and for building the smart city for smart people and by smart people, encouraging active citizen engagement in policy development and urban planning. The smart city strategy of Barcelona is empowering the citizens (Forster 2018). In 2015, Barcelona created several platforms for citizen participation in the technology and policy of the smart city (see Table 3).

Additionally, to improve the convenience of public services received by the citizens, City Council was created to allow the provision of services by public agencies remotely and mobile kiosks, where one can receive various certificates, publish a complaint, get necessary information, and so on (Nikitin et al. 2016).

All in all, the citizens are being offered more opportunities by new technologies to participate in the functioning of their communities. This enables the convergence of the physical and the digital-to-people. This is due to the fact that the digital changes can happen without heavy infrastructure, unlike the broad projects of the past that are determined by governments. Such changes can arise from bottom-up actions thanks to the right platforms through which people can transform the cities they belong to.

The challenge to resolve in developing data-driven sustainable smart cities that can benefit the quality of life of all citizens is that the tools we shape also shape us. In this respect, there is an increasing tendency to engage more citizens to take part in formulating policies through new technologies. It is clear that the citizenry as informed and

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Table 3 Platforms for citizen participation in Barcelona. Source: Bibri (2020a)

Fab Labs	Classrooms where citizens can learn about the principles and applications of digital technologies, and gain access to tools that allow them to innovate technologically and participate in smart city projects.
22@Barcelona	A space designed to attract startups and skilled innovators to develop new technologies leveraging the data produced by the city's extensive IoT infrastructure. This has led to several successful pilot projects, including mobility and parking.
Cisco Barcelona Co-Innovation Center	Enables close collaboration among local Cisco customers, governments, startups, academia, and developers to create new business models, innovative ideas, and technological solutions.
Decidim.Barcelona	A participatory democracy platform which allows Barcelona's citizens to see and discuss proposals put forward by the city government, and submit their own. Decidim is used to create Barcelona's government agenda, with over 70% of proposals coming directly from over 40,000 participating citizens.

empowered through the Internet is increasingly making a difference as new forms of data and advice are being implemented by means of different participative and interactive platforms. Mobile and other applications are giving rise to new forms of preference elicitation, marking profound changes that need to be mobilized through the equally powerful big data science and analytics that advanced ICT will offer.

Urban planning

The use of the data-driven approach to urban planning, the analysis of the data related to the population, allows London and Barcelona to consider the emerging demand for various venues. In other words, the application of the data-driven technology in planning is associated with the planning of districts, streets, as well as urban infrastructure based on the collection of information on the movement of residents and activities. The Mayor's Smart London Plan developed in 2013, which outlines how big data technologies can be used to improve citizens' lives and includes measurements of success and targets accordingly, was updated in 2016, outlining the progress in different city areas (Pozdniakova 2018). According to the Smart London Plan, the city plans to "promote smart approaches through London's planning system—maximize the use of data to guide the planning and design of London, including in London's opportunity areas, and encourage developers to adopt a more consistent approach to deploying digital infrastructure to future proof new developments" (London City 2018, p. 11). Sustainable urban planning should involve the integration of information on the expectations and uses of the residents of the different districts of the city in the construction of scenarios in response to the need for urban renewal, redevelopment, and development. Such integration makes it possible to improve the way the districts meet the needs of their inhabitants and to associate and share environmental and social practices and enhance participation and dialogue with the residents.

In relation to planning in general, among the core questions that could broaden our knowledge on how data-driven sustainable smart cities can harness their potential through the underlying strategies and solutions are (Bibri 2020a):

- At what stage of the planning process should environmental, economic, and social concerns introduced, and what kind of measures are needed to have an effective integration of such concerns early on?

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- To what extent can advanced technologies support joined-up planning, a form of integration and coordination which enables system-wide sustainability effects to be tracked, understood, analyzed, and built into the very responses and designs characterizing the operations and functions of the data-driven sustainable smart city?
- What kind of advanced technologies are available that can be implemented to make the planning process more dynamic based on constantly updated information on the operations and functions of the data–driven sustainable smart city?
- To what extent can the aggregation of real-time data contribute to dealing with changes in the data-driven sustainable city at any spatial and time scale, especially datasets can show the real-time functioning of the city and provide deep insights into how long term changes can be detected?
- To what extent can short–termism in urban planning, which entails measuring, evaluating, modelling, and simulating what takes place in the city over hours, days, or months, change the way the data-driven sustainable smart city functions as to focusing on sustainability problems and issues much more in the short term than hitherto?
- What is the potential of using urban intelligence functions to capture how the data-driven sustainable smart city is changing in its nature on the basis of its real-time functioning and becomes able to exploit and integrate complexity science, urban science, and big data science in constructing new powerful forms of urban simulations models and optimization and prediction methods that can generate more effective urban structures, forms, and scales?

With respect to the latter, urban intelligence and planning functions envisaged for the data-driven sustainable smart city as related to its processes and practices should be woven into the fabric of existing institutions whose mandate is advancing sustainability, optimizing efficiency, strengthening resilience, improving equity, and enhancing the quality of life for citizenry.

In sum, the data show the contours of a goal hierarchy in the data-driven sustainable smart city. Environmental and economic concerns are at the top of the goal hierarchy supporting the strategies of such city. In other words, the environmental and economic goals of sustainability dominate over the social goals of sustainability. The environmental and economic dimensions of sustainability is at the core of the agenda of urban development for London and Barcelona. This is a shortcoming since the social aspects are highly important in the urban context. Smart London Strategy Officer Dr. Stephen Lorimer said: “A lot of us fall into the trap of focusing on the environmental side of things but smart city development gives us an opportunity to be cross-cutting and address all three dimensions of sustainability” (Forsdick 2019a). The hierarchy of sustainability goals could reflect the challenge of incorporating social issues into a data-driven technology–led approach. These cities need to develop a broader agenda entailing an amalgam of environmental, economic, and social concerns. And in order to fully achieve their goal of becoming data-driven sustainable smart cities, the social aspects of sustainability need to be supported by planning practices and concrete development strategies.

Big data applications are associated with the three dimensions of sustainability in terms of enhancing and advancing urban processes and practices (Bibri 2019b,

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2020a). Smart London Strategy Officer Dr. Stephen Lorimer said: "We need to build up a picture of what people's needs are in the city and how we can deliver a sustainable and fair city from that …. Data is the best way of articulating those needs, but we need to develop more than just our data sharing and data analytics—we need collaboration across environment departments and London Boroughs … We have been looking into opening up the data that are held by commercial and residential property owners to build a building stock model for London. The data can be used to develop good designs and master planning to increase social, economic, and environmental sustainability" (Forsdick 2019a).

Data-oriented competences

At the core of data-driven sustainable smart cities are various technical and institutional comptences, i.e., the set of demonstrable characterisitics and abilities that enable and improve the efficiency and performance of urban operational functioning, management, and planning as a collection of interrelated processes and activities. These competences are key features of London and Barcelona as illustrated in Table 4.

Urban operating systems/horizontal information platforms

Urban operating systems serve to link together diverse smart technologies to coordinate urban systems and domains. Smart cities represent constellations of instruments across many scales that are connected through multiple networks augmented with intelligence, which coordinate continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the physical, environmental, economic, and social forms of the city. Examples of city operating systems or control rooms include Microsoft's CityNext, Urbiotica's City Operating System, IBM's Smarter City, and PlanIT's Urban Operating System, with the latter representing Enterprise Resource Planning (ERP) systems as intended to operate and coordinate the activities of large companies repurposed for cities (Bibri 2019b). Accordingly, this kind of instrumentation is the domain of the ICT industry that is offering the detailed hardware and software to provide the operating system for smart cities.

Barcelona is recognized for its best practices in accordance with the notion of the data-driven city. Horizontal information platforms, a form of city operating systems which aggregate and standardize the flows of functional data for their subsequent integrated analysis, operate in Barcelona under Sentilo and City OS. Sentilo, an open (data source) platform which connects all the sensors installed in the city and integrates all

Table 4 Data-oriented competences of London and Barcelona. Source: Adapted from Nikitin et al. (2016)

Competences	London	Barcelona
Analytical centers	• Smart City Board	• Big Data Center of Excellence
Horizontal information systems	• System implemented partially/pilot	• City OS • Sentilo
Training centres and programmes, urban information studies institutes	• City Univercity London • College London • Tech City Institute	• Institut Municipal d'Informatica

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the data obtained from these sensors, constitutes a source of data for City OS. This open system in turn integrates and processes all the data obtained from systems of state control (traffic, mobility, energy, noise level, etc.), state agencies (schools, hospitals, cultural institutions, etc.), business environment, municipal sources, and various detectors and cameras. City OS project was developed in 2013 to solve the problems of data disconnection. Application developers can leverage Sentilo to gain access to sensor data in a more structured and convenient manner. Sentilo has been successfully deployed by other city councils that followed the lead of Barcelona. Similarly, a horizontal information platform in London has recently been developed at London DataStore (Bibri 2020a). This is one of the first platforms to make public data open and accessible, and has been operating since 2010. Open data are at the center of London's transition into a smart city (Card 2015). However, Ferro and Osella (2013) provides an overview of different open data models that can be used by municipalities or governments to release a variety of administrative and operational data.

The introduction of a horizontal information platform that integrates all the systems and technological solutions that are used in all the departments of Barcelona and London is a key solution to one of the significant challenges concerning the implementation of the data-driven approach to the smart city. This challenge pertains to the sectoral fragmentation of the deluge of urban data. The flows of this deluge generated by various functional departments is analyzed in isolation, whereas urban problems are of a complex and wicked nature and thus requires a rather comprehensive solution. The situation is usually compounded by the self-contained and unconnected nature of the technological solutions and information systems used in the different departments of the city.

Urban operations centers, dashboards, and strategic planning offices

Generally, urban operations centers and urban dashboards are intended to draw together and interlink urban big data to provide an integrated view and synoptic intelligence of the city (e.g., Bibri 2019b, 2020a; Kitchin 2014; Kitchin, Lauriault, and McArdle, 2015). Urban operations centers are typically created to monitor the city as a whole; pulls or draws together real–time data streams from many different city agencies and departments (including public transport and traffic, mobility, power grid, municipal and utility services, emergency services, weather feeds, information sent in by the public via smartphones, and social media networks) into a single data analytical center; and then process, analyze, visualize, and monitor the vast deluge of live service data for real-time decision-making and problem solving.

Analytical centers have been established and currently operate in both Barcelona under Big Data Center of Excellence as well as in London under Smart City Board. As to Barcelona, the center is committed to create innovative platforms for the promotion of big data use and application, the introduction of big data technologies, and the provision of expert assistance (Nikitin et al. 2016). It was also planned to open Cisco innovation center for the Internet of Everything in 2026. As regards London, the Smart London Board, which involves industry experts, entrepreneurs, and thought leaders, was set up to support the city authorities in visioning, strategizing, and applying smart city objectives (Bibri 2020a; Eden Strategy Institute 2018). In addition, the London

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Fig. 4 CASA's London City Dashboard. Source: http://citydashboard.org/london

DataStore plays an important role in overcoming city challenges, allows keeping citizens up-to-date, and helps to create applications based on the raw data available thanks to the open access to the public data that are being used to control, regulate, and plan the city. According to the Smart London Plan (2018, p. 6), the London Datastore "has engaged London's developer community and resulted in numerous apps that help the city to function better. We will build on this work to identify and publish data that addresses specific growth challenges, with an emphasis on working with companies and communities to create, maintain, and use these data."

Urban dashboards generate visualisations that help both expert and no-expert users interpret and analyze information. In London, city dashboards communicate live feeds of real-time data to citizens. As illustrated in Fig. 4, citizens can be informed in real-time about the weather, air pollution, public transport delays, electricity demand, public bike availability, traffic, and so on. The London dashboard as a visualisation site relies on data, though not in real-time, to track the performance of the city with respect to a number of areas—including, but not limited to, transport, environment, communities, housing, health, jobs and economy, and policing and crime (Kitchin 2014).

In the context of data-driven sustainable smart cities, which develop and use a sort of integrated, real-time urban data analytics, analytical centers, dashboards, and applications

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provide a powerful means for not only making sense and conceiving of, living in, and managing the city in the here-and-now, but also for planning the city in relevance to sustainability. Planning involves, among others, envisioning future scenarios as regards how the city should perform sustainably on the basis of data-driven technological solutions.

Strategic planning offices are key to urban development projects and endeavors, especially when it comes to sustainability. They are part of the competences of London and Barcelona in regard to applied data-driven technology. Both cities promote smart approaches through planning systems—make extensive use of data to guide urban planning and design and to encourage developers to deploy digital infrastructure to future proof new developments. Strategic planning and policy offices use a one-stop data analytic hub to bring and weave together data from a variety of city agencies and departments for the management and planning of the city in a more efficient and effective way (Bibri 2019b). Huge amounts of data stream daily through such offices for analysis in terms of cross–referencing data, identifying patterns, and recognizing and solving city problems.

Training programs and educational institutes

Specialized academic programs within data science and big data analytics related to urban science, urban computing, urban studies, urban analytics, and so on have gained widespread use in not only the Cities of London and Barcelona, but in many other cities in developed countries. Barcelona is one of the very few cities where the Institutes of Urban Computing have been established to study the city management issues in a systemic way using advanced big data analytics techniques, and a large number of educational programs with big data analytics disciplines and the introduction of technologies for city management are offered by universities and business schools (Nikitin et al. 2016). In London and Barcelona, numerous initiatives have, yet at varying degrees, been implemented to develop competencies in a number of areas related to big data analytics and urban informatics/science by educating citizens and accumulating relevant expertise thanks to the creation of the related centers. These involve conducting seminars and courses and providing trainings to improve the level of technological knowledge considering the solutions being implemented in the city and used by citizens. In addition, the Smart City Business Institute (SCBI) was set up in Barcelona to introduce what is known as smart education to elementary, middle, and high schools, offering hands-on workshops to help students develop mobile and robotic apps that attend to smart city challenges (Eden Strategy Institute 2018).

At the practical level, much needs to be done for big data analytics projects to become successful in terms of studying, managing, and planning cities. In fact, many of these projects are still having difficulties to deliver useful and concrete outcomes in this regard. This is due often to the poor management and utilization of available resources, in addition to the lack of the training of the data analysts. Big data science and analytics is a heavily applied field where the programs offered by academic institutions are inadequate for preparing the data scientists and analysts for the task (Bibri 2019d ; Donoho 2015).

Innovation labs/Research centers

Innovation labs and research centers are springing up everywhere, becoming commonplace across different cities. Within the scope of this paper, they indicate the degree of implementation of the data-driven city concept in terms of the extent to which the

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applied technology solutions are developed for urban operational functioning, planning, and management. Therefore, a number of cities in developed countries have established innovation labs and research centers, thereby stimulating actively the development of innovative solutions. These are known in London as ICT Labs and Future Cities Catapult, and in Barcelona as Cisco IoE Innovation Center and city districts (Nikitin et al. 2016). In this context, they serve as the ground for testing potential solutions for the management of the city. For example, ICT Labs are concerned with developing and implementing advanced solutions for urban management. In addition, the new London Office for Technology & Innovation (LOTI) was set up to understand, enhance and apply the leading city practices, as well as to integrate resources and expertise for the benefits of the whole city through collective intelligence (Bibri 2020a; Eden Strategy Institute 2018).

An innovation lab in this context denotes a working space designed to develop, test, and improve innovative solutions for sustainability in the form of urban intelligence functions. It is a unique environment devoted to building, advancing, and sharing practical knowledge and know-how in response to the needs and aspirations of the city and its stakeholders and citizens. It involves researchers, scientists, industry experts, business professionals, and citizens. The key strengths lie in the team's multidisciplinary knowledge and skills, long–standing experience, international expertise, and access to global networks in the sphere of sustainability and related technologies.

Generally, advanced ICT is being used to increase the efficiency of energy systems, optimize the performance of green technologies, enhance the delivery of public and social services, advance transport and traffic systems, and improve the quality of life, but to name a few. In this respect, the real challenge for modern cities is to explore the notion of data-driven sustainable smart cities as innovation labs. This entails developing novel intelligence functions for the city based on the IoT and big data technologies for enhancing urban practices in response to the challenges of sustainability and urbanization. Especially, the vision of the city functioning in real time is becoming increasingly achievable and deployable (e.g., Kitchin 2014; Rathore et al. 2018).

Table 5 provides a summary of the competences and related functions of the two emerging data-driven smart cities for improving different areas of sustainability.

Infrastructure and data sources

In the face of the escalating rate and scale of urbanization, we need not only to develop new urban fabric that can deal effectively with this growth, but also to make the best use of the existing infrastructural and informational assets to ensure that the increasingly large metropolises are sustainable by means of advanced technologies. In this respect, the IoT has been massively used to available resources of different kinds, buildings, and infrastructure without many engineering obstacles with existing cities.

There are different indicators of the readiness of a city as to the implementation of the data-driven city concept in smart urbanism. These indicators are associated with both the technical and institutional aspects of the city competences. The focus here is on the degree of the readiness of London and Barcelona from a technical perspective in terms of the availability and development level of the city infrastructure and data sources that are needed to generate and transmit data to the diverse city centers for

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Table 5 Data-driven smart city competences and related functions

Competences	Functions
Horizontal information platforms	• Linking together multiple technologies to enable greater coordination of urban systems and domains: - Connecting all the sensors installed in the city and storing and integrating all the sensed data - Aggregating and standardizing the flows of the functional and territorial data from the systems of state control, business environment, municipal sources, and numerous sensors and cameras for their subsequent analysis and visualization in 3D format - Reworking and repackaging the collected data for daily consumption by different city stakeholders - Allowing application developers to gain access to the sensed data in a more structured and convenient manner - Providing comprehensive solutions to complex urban problems by integrating the self-contained and unconnected technological solutions and information systems used in different functional departments • Improving the efficiency of the implemented applied technological solutions by means of the functionally compatible information platforms
Operations centers and dashboards	• Drawing together and interlinking real–time data streams to provide an integrated view and synoptic intelligence of the city: - Using visualization sites to help both expert and no-expert users interpret and analyze information, and to allow citizens to monitor the city for themselves and for their own ends - Relying on integrated, real-time data to track the performance of the city and to communicate the live feeds of real-time data to citizens with respect to a number of areas - Using automated systems to respond to citywide events by making immediate decisions pertaining to various urban areas - Overcoming urban challenges, keeping citizens up-to-date, and developing applications based on the standardized and published open data thanks to the horizontal information platforms • Creating innovative platforms, promoting big data use and application, introducing data-driven technologies, and providing expert assistance
Strategic planning and policy office	• Making extensive use of data to guide urban planning and design, and to encourage various developers to deploy digital infrastructure to future proof new developments • Using a one-stop data analytic hub to bring and weave together data from a variety of city agencies and departments in order to regulate and govern the city in a more efficient and effective way • Cross–referencing data, identifying patterns, and recognizing and solving city problems
Training and educational programs and institutes	• Providing specialized academic programs involving big data science and analytics within such domains as urban science, urban informatics, urban computing, urban analytics, and urban studies • Offering a large number of educational programs with big data science and analytics disciplines and introducing technologies for city operational functioning, management, and planning • Implementing initiatives for developing competencies in a number of big data science and analytics areas in relation to urban sustainability by conducting seminars and providing trainings to improve the level of technological knowledge in this regard
Innovation labs and research centers	• Creating multidisciplinary teams based on practical know how, long–standing experience, international expertise, and access to global networks • Enabling interaction and cooperation between scholars, researchers, industry experts, business professionals, and thought leaders to enhance research opportunities, academic excellence, real-world problem solving, and knowledge creation and dissemination • Developing and testing innovative technological solutions for urban operational functioning, management, and planning • Featuring the latest developments in urban technologies and solutions and demonstrating how they are applied in real-world settings • Developing urban intelligence functions for improving and optimizing urban operations, functions, services. designs, and strategies • Integrating resources and expertise for the benefits of the whole city through collective intelligence • Managing, analyzing and visualizing different kinds of urban projects • Supporting the city authorities in visioning, strategizing, and applying smart sustainable city targets and objectives

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Table 6 Infrastructure and data sources rating

Infrastructure	*Unit*	*Barcelona*		*London*	
		Value	Score	Value	Score
1. Accessibility	Average mark		2.4		3.3
1.1. Density of the city Wi-Fi network	Pcs. / km^2	5.79	4	No[2]	1
1.2. Share of households with internet access	%	70	2	94	5
1.3. Usage and coverage of mobile packet communication for citizens of the city	%	65	2	95	4
1.4. Level of penetration of the fibre-optic network	Rating value[1]	100	5	21	2
1.5. Number of Wi-Fi hotspots in private and corporate segments	Rating value	72	2	100	5
1.6. Tariffs for broadband Internet connection as a percentage of GDP per capita	Rating value	93	1	99	4
1.7. Tariffs for mobile Internet as a percentage of GDP per capita	Rating value	74	1	86	2
2. Quality	Average mark		2.0		5.0
2.1. Speed of fixed broadband in private and corporate segments	Mbps	16	3	25	5
2.2. Network capacity	Values in the rating	5	1	84	5

Sources	*Unit*	*Barcelona*		*London*	
		Value	Score	Value	Score
1. Open data and electronic payments	Average mark		2.3		4
1.1. Open data (OD) and online presence	Rating value[1]	84	3	100	5
1.2. Electronic and mobile payments	Rating value	331	2	930	4
1.3. Number of data sets on the OD portal	Pcs.	48	2	66	3
2. Residents	Average mark		2.4		3.6
2.1. Social network use	Rating value	59	1	91	5
2.2. Internet use as a percentage of the population	Rating value	83.7	3	90	4
2.3. Level of mobile penetration	Rating value	24	3	35	4
2.4. Proportion of computer owners	Rating value	74	2	90	5
2.5. Proportion of broadband internet subscribers in the private sector	%	84.5	4	59	1
2.6. Proportion of residents who own smartphones	%	59	2	89	5
2.7. Number of visitors of municipal services web-portal		24	2	4	1
3. Sensors and surveillance cameras	Average mark		4.8		4.5
3.1. Road traffic	Availability	Y	5	Y	5
3.2. Public transit	Availability	Y	5	Y	5
3.3. Parking	Availability	Y	5	Y	5
3.4. Electricity grid	Availability	Y	5	Y	5
3.5. Street lighting	Availability	Y	5	N	0
3.6. Cleaning and waste disposal	Availability	Y	5	Y	5
3.7. Air	Availability	Y	5	Y	5
3.8. Exhaust emission control	Availability	Y	5	Y	5
3.9. Water	Availability	Y	5	Y	5
3.10. Density of CCTV cameras	Pcs. / km^2	32.2	3	318.1	5

Source: Nikitin et al. (2016)

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analysis and then the deployment of the obtained results for various uses and applications in terms of decision-making. Nikitin et al. (2016) compare London and Barcelona using statistical analysis and expert assessment of technology implementation in terms of the degree of theirreadiness. Their results are presented in Table 6. The readiness of some elements were assessed based on the results of the Networked Society City Index rating from Ericsson. The higher the value is, the higher the level of the rated indicator.

It is worth noting that the sensor infrastructure is largely developed proportionally in London and Barcelona. A most popular form of government-sponsored Internet access is seen in the form of public Wi-Fi areas around the city. The Barcelona City's Wi-Fi has been built for quite sometime. Within the framework of the development of the city Wi-Fi in Barcelona, 590 spots among them 220 in parks have been installed only until 2016, and the number is planned to increase to 1520 new spots in order to extend the Wi-Fi network to cover all buses and underground (Nikitin et al. 2016). According to Eden Strategy Institute (2018), Barcelona has declared its intentions to become the most connected city in the world and it is following through on its promise by investing considerably in the IoT infrastructure and applications for the city. A city Wi-Fi can have a significant impact on the communication capabilities of the sensor infrastructure and the data transfer system. As regards the IoT sensors and the city's open data platform, Barcelona therefore has a dense network of sensors which compile data from a wide variety of sources. Barcelona has brought the IoT to life (Adler 2016).

There is a range of the ICT architectures that essentially aim to provide the appropriate infrastructure for the operation of the IoT and Big Data ecosystem in relation to large–scale technological solutions within smart cities. These city architectural designs tend to follow similar patterns in terms of layers. However, Sinaeepourfard et al. (2016) analyze Barcelona as a smart city, with special emphasis on the layers responsible for collecting the data generated by the sensors deployed across the city. The authors estimate the amount of the data transmitted daily via sensors through the network, and make a rough projection based on the assumption of an exhaustive deployment that fully covers the whole city. They state that the Barcelona City Council and Municipal Institute of Informatics (MII) jointly cooperated in 2012 to set the basics of an architecture defining the strategies and policies allowing Barcelona to become a Smart City. The design of the Barcelona Smart City IT architecture entails three main layers, namely the Information Sources layer, the Middleware layer, and the Smart Applications layer (see Fig. 5).

A successful system enabling the functioning of the data-driven smart city can be divided in three levels, namely:

- The infrastructure that collects the data within the framework of the city. This level includes technologies and solutions allowing the collection and transfer of the data for their further processing and analysis. Here the standardization of the data infrastructure and the data integration in a unified system are important for facilitating further usage and processing of the data (e.g., Sentilo).
- The tools dedicated for storage, management, processing, and analysis of the data collected by the system (e.g., City OS).
- The exchange of the data among all the interested parties and the adoption of solutions based on the analysed data. This level includes platforms with open data and tools of data visualization (e.g., dashboards) applied by the city administration

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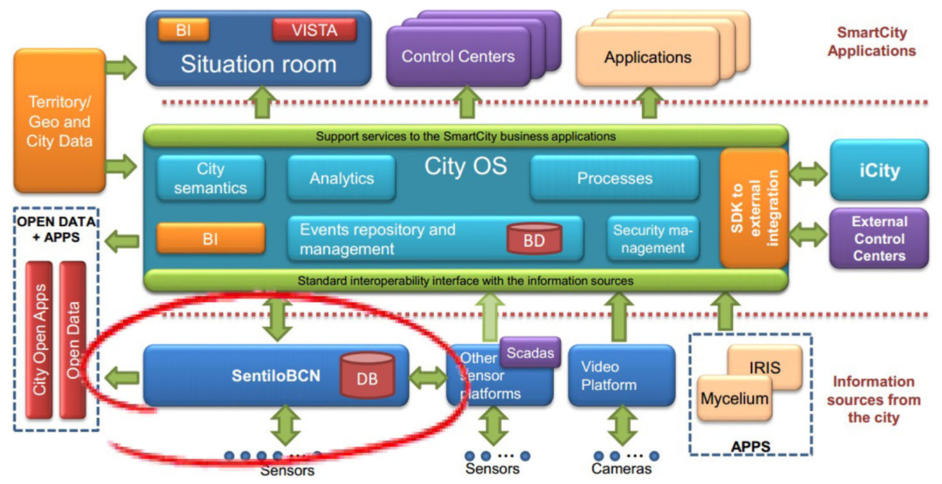

Fig. 5 Barcelona Smart City IT architecture. Source: Sinaeepourfard et al. (2016)

> for control over the city management system, automated systems of response to city-wide events related to various urban systems (e.g., situation room and control centers), as well as a number of applications (e.g., service agencies and other developers).

The plan of London City (2018) is to ensure that it has one of the fastest wireless networks in the world and invests in free Wi-Fi in order to offer a smarter experience to all citizens. It has launched the fastest free Wi-Fi in all of UK with a multi-million-dollar investment, offering fast Internet speeds at 150 points across the city (Eden Strategy Institute 2018). London has 5969 public Wi-Fi hotspots across Greater London, and invested USD 2.32 million through the Super Connected Cities Program to offer indoor public Wi-Fi in Galleries and Museums (Eden Strategy Institute 2018). Indeed, London is leading as to the quality and availability of the broadband and mobile Internet compared to Barcelona. It is also leading in regard to the level of data disclosure: making public information known and accessible, particularly for improving sustainability in the city. London DataStore publishes open data from different departments of the city administration, and aggregates all data available on functional and territory data, analyze them, and visualize the results in 3D format. In London, the data are used most rapidly for making decisions pertaining particularly to transport management. The open data published by the transport administration entail the data that are collected in the real time mode, and the data obtained from various different operators are standardized and then published on the open data portal (Unified API) to be used by numerous developers of mobile applications, especially transport and mobility (Nikitin et al. 2016).

\In addition, in London around 78% of adults own a smartphone, 90% of population have access to the internet, free Wi-Fi are provided for over 80 public buildings and libraries, 40,000 businesses are digital, and 200,000 employees work in technology sector, high-speed affordable digital connectivity is a priority for the city (Pozdniakova 2018). Indeed, London is leading compared to Barcelona in terms of accessibility as a key feature of the city infrastructure as shown in Table 6. Furthermore, the government of London has defined rules and guidelines for its open data platform to work with public and private sector organizations, enable common data standards, identify and prioritize

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data needs, protect privacy, and guarantee a transparent use of data (Eden Strategy Institute 2018).

On the whole, both cities are finding multiple benefits to connecting devices and collecting a plethora of data that can be translated into meaningful insights to guide the cities' daily decisions. According to Cisco's estimates, Barcelona's current smart city investments should return a cumulative economic benefits of USD 970 million by 2026. So far, the IoT systems have saved Barcelona about USD 58 million on water, generated USD 50 million per year in parking revenues and generated 47,000 new jobs (Eden Strategy Institute 2018).

However, while modern technologies are adequately introduced for efficient and sustainable solutions within common areas of city management in the two cities, e.g., numerous methods applied for reducing the negative impact on the environment and lowering energy consumption, there still is a need for more applied technologies that can aid the city authorities in using the data to the full extent to make and enhance decisions related to sustainability. Generally, a colossal amount of the data needed to make a city sustainable smart is indeed already available, butit is simply a matter of knowing how to understand and exploit these data.

Discussion

The study has identified the core dimensions of the data-driven smart city based on combining and comparing London and Barcelona as the leading data-driven smart cities in Europe. Moreover, it has shown how these cities are utilizing data-driven technology solutions to improve their contribution to the different areas of sustainability. The data-driven sustainable smart city can be implemented on different spatial scales and within different urban systems and domains. This depends on the degree of technology development with respect to the instrumentation, datafication, and computation that need to pervade the urban environment, and how and to what extent these technological elements are leveraged in the transition towards sustainable development. As the two cities share and vary in these aspects, combining practical initiatives from both cities is meant to be of complementarity in the sense that these cities can improve each other's qualities and learn from each other's experiences.

From a comparative perspective, the comparison of London and Barcelona concerns the relative proportions of the implementation of big data technologies and the use of data-driven solutions in city systems and domains in the context of sustainability. In other words, this comparison focuses on the kind of problems and challenges that the two cities face, and what this entails in terms of the technologies they adopt based on the solutions they prioritize in regard to sustainability. Otherwise, the enabling, integrative, constitutive, and ubiquity nature of advanced ICT makes the latter applicable to different urban contexts in terms of the development, deployment, and management of big data technologies and their applications, irrespective of the complexity of physical, environmental, economic, and social systems of the city.

Worth pointing out is that every city has its specific opportunities, capabilities, and constraints, not least in relation to the application of advanced technologies for sustainability. Hence, there are many things for cities to learn from each other as regards the knowledge and expertise available in this regard. It is therefore crucial to investigate the innovative solutions and successful practices of different data-driven sustainable smart cities based on the ongoing and future endeavors and projects in their local

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context, and then compile and distill the results into a unified outcome that contributes to forming a basis for a model of urbanism that can be applied by different cities based on their own circumstances. This is one of the objectives that is intended to be achieved from conducting this study by comparing and combining London and Barcelona in their effort for becoming data-driven sustainable smart cities. In this context, lessons can be learned from both cities, particularly in relation to data-oriented competences. Especially, it is widely recognized that there cannot be a set of rigid strategic guidelines or strict solutions to be implemented anywhere around the world to achieve urban sustainability. Indeed, sustainability to a certain extent depends on several intertwined factors, which are usually shaped and influenced by the national and local contexts. Accordingly, the local opportunities, capabilities, and constraints of each city need to be dealt with in a more integrated given the complexity of urban systems in terms of their political, social, economic, and environmental dimensions.

Moreover, no attempt has, so far, been undertaken to establish any 'data-driven sustainable smart city' indexes, nor is there a single conceptual unit or analytical proposition of such city. To put it differently, there are as yet no cities that could be assessed by experts or scientists so to be able to unanimously assume basic standards of the data-driven sustainable smart city. Also, the heterogeneity of the concept of sustainability and the constant change of technological landscape remain problematic for the practical implementation of policies related to such city. There are no policy documents that provide concrete guidelines for global implementation. Accordingly, each city should deal with its own planning and development in the sense of designing the data-driven sustainable smart city, applying its solutions, adopting its strategies, and implementing its policies to improve the quality of life of its citizens. To add, indeed, city authorities, scientific communities, and industry experts have no common agenda of action.

Furthermore, data-driven sustainable smart cities as a holistic approach to urbanism is opening entirely new windows of opportunities to advance sustainability by using advanced technologies to enhance the process and practice of sustainable development. Among the most urgent issues they deal with are:

- Transport efficiency and management
- Traffic congestion
- Urban infrastructure management and resilience
- Security and safety
- GHG emissions
- Services enhancement
- Equal access to education, health, and other social services
- Citizen participation in urban management and planning

Big data technologies provide significant opportunities for transforming urban sustainability due to the huge potential of their novel applications that usher in intelligence in nearly all city systems and domains. In this respect, Bibri (2019b) highlights and substantiates the great potential of big data analytics for increasing the contribution of sustainable smart cities to environmental, economic, and social sustainability by identifying numerous practical applications of big data technology in relation to a number of urban systems and domains. The advantages of this advanced technology lie in

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how significantly it will influence sustainable smart cities and their citizens. Besides, the core enabling technologies of big data analytics will in the near future be dominantly used for monitoring, understanding, analyzing, and planning smart cities to improve their health and the life of their citizens. The emerging data-driven approach to smart urbanism is changing the way we understand, plan, and govern cities, both within and across city domains (Bibri 2019b, 2020a; Kitchin 2015; Kitchin, Lauriault, and McArdle, 2015; Townsend 2013),, The linking and integration of diverse forms of urban data provide a deeper, more holistic analysis, which makes it possible to control, manage, and regulate urban life on the basis of evidence-based facts, particularly in relation to sustainability, efficiency, resilience, equity, and the quality of life.

In addition, data-driven sustainable smart cities involves a number of data-oriented competences that need to be developed to enable the wide use of data-driven technological solutions in urban operational functioning and management as well as urban planning and development. These competences include urban operating systems, urban operations centers, urban dashboards, innovation labs, research centers, and training centers and educational institutes. One of the key innovations being utilized by these centers is open data movement, a form of data sharing among city actors in an attempt to improve many aspects of urban living. However, most of the identified data-oriented competences have partly been addressed by several studies in relation to smart cities of the future (e.g., Batty et al. 2012; Kitchin 2015, 2016; Townsend 2013), data-driven smart sustainable cities of the future (Bibri 2019a, b, 2020a), real-time cities (e.g., Kitchin 2014), and data-driven cities (Nikitin et al. 2016).

The idea of building data-driven sustainable smart cities is becoming a reality thanks to the recent advancements in both urban development practices as well as technological solutions. As with many emerging data-driven smart cities across the globe, London and Barcelona are increasingly pervaded with various forms of the IoT, namely sensors, platforms, infrastructures, applications, and networks that produce colossal amounts of data. This deluge provides rich streams of information about many aspects of urbanity, enables real–time analysis of urban dynamics, and facilitates new ways of how the city can be managed and planned. However, the IoT is known to involve significant security risks. A major hindrance in the broad integration of IoT in smart cities lies in its security. The IoT is inherently networked and ubiquitous. The larger the networks, the higher the security risks. Therefore, it is important to have secure IoT devices, platforms, applications, and infrastructures to avoid major catastrophes associated with massive breaches or attacks. Smart city technologies raise a number of cyber-security concerns that require careful consideration and special attention, although successful cyberattacks on cities remain relatively rare (Hashem et al. 2016). Most of the smart city strategies fall short in considering security risks. Such disregard can be attributed to the ambiguities in government laws and the lack of institutional and organisational policies (Almeida et al. 2017). Several studies have addressed security risks and proposed potential solutions to mitigate them in smart cities. For example, Lacinák and Ristvej (2017) provide insights into the importance and use of modeling and simulations to address security issues. Khanac et al. (2017) identify a comprehensive list of stakeholders and modeled their involvement in smart cities by using the Onion Model approach, providing a secure service provisioning framework in smart cities. To guarantee a successful implementation of the IoT in smart cities, solving

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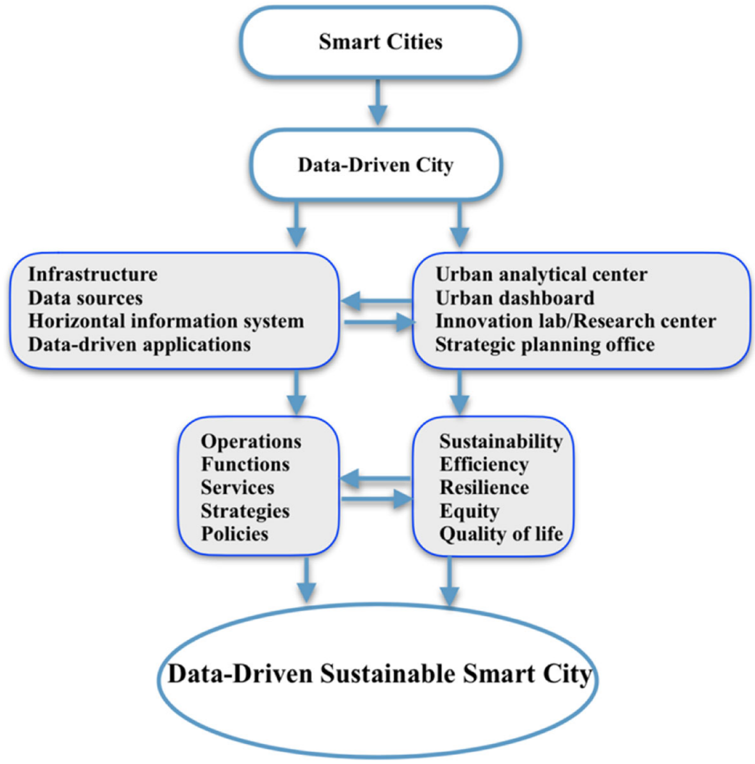

Fig. 6 A conceptual framework for data-driven sustainable smart cities

security issues must be given priority in the IoT realm. All in all, to deal with security issues requires both technical and socio-political solutions.

On the whole, this study has identified different themes, i.e., technologies, applications, competences, infrastructure, and data sources that are related to data-driven sustainable smart cities. The data collected from different sources show that different themes produce distinguished models of data-driven sustainable smart cities. One of the key factors determining the distinction between these models is the extent to which the goals of sustainable development are supported in the operation, management, planning, and development of the city. This entails the level of the development of different technological components and their implementation to improve and advance sustainability.

The integrated framework (Fig. 6) is derived from the results of the two cases investigated. Hence, its essential elements are based on the emerging paradigm of smart urbanism in terms of its data-driven and sustainable strands. As such, it attempts to capture in a structured manner the core dimensions of the data-driven sustainable smart city. In this respect, there are four basic categories of criteria that are used here in defining such city, namely technologies, competences, processes and practices, and sustainability and smartness. In addition, this framework represents a conceptual structure intended to serve as a guide for building different models of data-driven sustainable smart cities.

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Conclusion

Big data technologies are certainly enriching our experiences of how cities function. And they are offering many new opportunities for more informed decision-making with respect to our knowledge of how to monitor, understand, analyze, and plan cities more effectively. Whether these developments will be to our collective advantage or disadvantage is yet to be seen for there is undoubtedly a dark side to all technological developments. Regardless, many smart cities across the globe have embarked on exploring and unlocking the potential of big data technologies for addressing and overcoming many of the pressing issues and complex challenges related to sustainability and urbanization. London and Barcelona are seen as exemplary practical initiatives in data-driven sustainable smart urbanism on national, European, and global scales. This study has been carried out as a demonstration endeavor of what these two cities are renowned for in this regard, with the aim of being exposed to general lessons. It has been worth illustrating the potential underlying the development and use of big data technologies for advancing sustainability.

The aim of this paper was to investigate how the emerging data-driven smart city is being practiced and justified in terms of the development and implementation of its innovative applied solutions for sustainability. This study shows that these cities have a high level of the development of the applied data-driven technologies, but they slightly differ in the level of the implementation of such technologies in different city systems and domains with respect to sustainability areas. They also moderately differ in the degree of their readiness as to the availability and development level of the competences and infrastructure needed to generate, transmit, process, and analyze large masses of data to extract useful knowledge for enhanced decision making and deep insights pertaining to urban operational functioning, mangement, and planning in relation to sustainability. Barcelona has the best practices in the data-oriented competences, whereas London takes the lead in regard to the ICT infrastructure and data sources.

Furthermore, the data–driven sustainable smart approach to urbanism as practiced by the two cities is justified by its ability to contribute, at varying degree, to the different areas of sustainability. However, the environmental and economic goals of sustainability dominate over the social goals of sustainability with respect to the development and implementation of the data-driven smart solutions for urban processes and practices.

Given the enabling, integrative, constitutive, and ubiquity nature of big data technology as an advanced form of ICT, coupled with the universality of urbanization and sustainability as major global shifts at play today, the findings of this study can be generalizable and thus applicable to other cities in terms of the implementation of data-driven technology solutions for the management of the city. In regard to the specificity of the findings of this study, the focus should be on the kind of applied solutions other cities should prioritize based on the challenges they face as to sustainability and urbanization, as well as their financial resources and technological capabilities. Still, to successfully implement and manage big data technology requires a holistic perspective so as to be able to identify and manage gaps and conflicts, as well as to harness synergies between different technological components with respect to functionality, ownership, access, and governance.

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This research enhances the scholarly community's current understanding of the emerging phenomenon of the data-driven city with respect to the untapped synergic potential underlying the integration of smart urbanism and sustainable urbanism for improving sustainability. Highlighted by this research is the interplay between these two approaches in terms of producing combined effects that are greater than the sum of their separate effects as regards the benefits of sustainability thanks to the big data revolution. Previous studies have long criticized smart cities for falling short in incorporating the goals of sustainable development in their strategies, and, more recently, for overlooking the role of data-driven solutions in sustainable development. This study draws special attention to the benefits of the emerging paradigm of big data computing as to transforming the future form of smart cities in relation to sustainability. Furthermore, this study will help strategic city actors understand what they can do more and invest in to enhance the sustainability performance of their cities on the basis of the applied data-driven solutions. It will also give policymakers an opportunity to identify areas for further improvement while leveraging areas of strength as to the data-oriented competences and infrastructure.

We hope that this study has produced the kind of the results that will be useful in directing further research by providing the grounding for more in–depth investigation on data-driven sustainable smart city development. We would particularly like to encourage qualitative research of the kind that we have attempted, which try to illuminate the core dimensions of the data–driven sustainable smart city and the assumptions and claims behind related initiatives. The rationale for this is that as the demand for practical ideas from the technological advanced nations about how to meet the requirements of sustainability through data–driven smart urban development increases, those initiatives are likely to attract attention from strategic urban actors around the world. Further research should focus on providing the knowledge that such actors will need to make informed decisions about how to achieve the objectives of data-driven sustainable smart cities in their own context. By investigating the two cities, we sought to offer models of big data technology-led urban transformation for other cities to learn from. Moreover, as this study has demonstrated that applied technological solutions already exist across the selected cities, it would be extremely useful to conduct a wider and more varied comparison involving cities from other European countries and from the rest of the world with a view to revealing more general trends in urban planning and development. In addition, a sequel to this work and thus part of our own future research is to integrate the data–driven smart city, the eco–city, and the compact city as the leading paradigms of urbanism into a novel model in order to improve and advance sustainability. This is one among many opportunities that can be explored towards new models of sustainable cities, predicated on the assumption that there are multiple pathways to and strategies for achieving the vision of sustainable development. Lastly, we believe that the outcome of this study can help advance the understanding of how the smart city phenomenon is evolving and adapting to new global shifts, especially in regard to sustainability.

Abbreviations

CCTV: Closed-Circuit Television; ERP: Enterprise Resource Planning; GHG: Green House Gases; GPS: Global Positioning Systems; ICT: Information and Communication Technology; IoT: Internet of Things; LED: Light Emitting Diode; LOTI: London Office for Technology & Innovation; MII: Municipal Institute of Informatics; MODA: The Mayor's Offices of

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Data Analytics; MOTI: The Mayor's Offices Technology and Innovation; NFC: Near-Field Communication; RFID: Radio Frequency identification; SCBI: Smart City Business Institute; ULEZ: Ultra Low Emission Zone

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