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Implementing Data-Driven Smart City Applications for Future Cities

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Abstract: Cities are investing in data-driven smart technologies to improve performance and efficiency and to generate a vast amount of data. Finding the opportunities to innovatively use this data help governments and authorities to forecast, respond, and plan for future scenarios. Access to real-time data and information can provide effective services that improve productivity, resulting in environmental, social, and economic benefits. It also assists in the decision-making process and provides opportunities for community engagement and participation by improving digital literacy and culture. This paper aims to review and analyze current practices of data-driven smart applications that contribute to the smooth functioning of urban city systems and the problems they face. The research methodology is qualitative: a systematic and extensive literature review carried out by PRISMA method. Data and information from different case studies carried out globally assisted in the inductive approach. Content analysis identified smart city indicators and related criteria in the case study examples. The study concluded that smart people, smart living, and smart governance methods that have come into practice at a later stage are as important as smart mobility, smart environments, and smart economy measures that were implemented early on, and cities are opening up to new, transparent participatory governance approaches where citizens play a key role. It also illustrates that the current new wave of smart cities with real time data are promoting citizen participation focusing on human, social capital as an essential component in future cities.

Keywords: smart cities; future cities; data-driven applications; smart applications; smart city indicators; digital literacy; digital culture

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1. Introduction

Cities contain 54% of the world's population and this number is expected to increase to 66% by 2050 [1]. This projected growth has led to investment plans in infrastructure for transport, water, electricity, and telecommunications to be estimated at $53 trillion from 2010 to 2030 [2]. Climate change will have severe repercussions for many cities, and resilience to both natural and man-made disasters continue to be an area of great concern [3]. In response to these major challenges, cities face increasing environmental stress and infrastructure needs, together with growing demands from residents to deliver and achieve a better quality of life [4,5].

There is a global drive to incorporate technology to improve functions and performances of urban cities. Since 1990, the development of the World Wide Web (WWW) and Information Communication Technologies (ICTs) have created opportunities for communication, engagement, and information sharing by local, regional, and national [6]. Many international institutions and forums believe in an ICT-driven form of development. The Intelligent Community Forum [7], for example, produces research on the local effects of the ICT revolution, and it now has a global spread. Many countries, especially European, have dedicated efforts to formulating strategies for achieving urban growth in a "smart" way for their metropolitan areas [8]. The role of innovation in ICT sectors is recognized, providing toolkits to develop and identify indicators, thus shaping a sound framework of analysis for researchers for urban innovations [9]. These innovations have resulted in introducing smart city movements, which have become an important part of the urban agenda and discourse [10,11]. Smart city is understood to be a fuzzy concept [8], and literature on smart cities provides several characterizations. A sustainable process of urban transformation into a smart city requires co-operation of many agencies, support by ICT infrastructures, and the integration of sustainable development, green growth, and collaborations between multi-stakeholders on multiple levels. The relationship between ICT infrastructure and economic performance has been extensively researched [12]. Other definitions stress the role of human capital and education in city growth [13], and they illustrate that the most rapid urban growth rates have been achieved in cities where an educated labor force is available. Berry and Glaeser [14] modeled the relationship between human capital and urban development by assuming that innovation is driven by entrepreneurs who innovate in industries and products that require an increasingly more skilled labor force. Holland [15] states that a smart city is utilization of networked infrastructure to improve economic and political efficiency that enable social, cultural, and urban development. Social and environmental sustainability is a major strategic component of smart cities, and smart city projects have illustrated a strong focus on achieving social inclusion of various urban residents in public services [16]. Researchers and policy makers have given attention to equitable urban growth, the extent to which social classes benefit from a technological integration of their urban fabric, together with "soft infrastructure" that includes knowledge networks, voluntary sector, safe urban environments, and night entertainment economy [17]. Smart cities also give attention to the role of social and relational capital in urban development. Communities need to learn, adapt, and innovate [18] and be able to use technology to benefit from it, which refers to the absorptive capacity [8], a concept that has been applied to different economic relations at different levels of spatial arrangements in cities [19].

Current and future cities have the potential to generate vast amounts of real-time data due to complex physical infrastructure and social networks [20] that are supported by data-driven applications. Due to the accessibility of real-time data, individuals and communities are increasingly presented with opportunities to engage in a variety of issues and processes that concern their lives. People form the nucleus of the city, and such opportunities have the potential to promote digital literacy and digital culture among citizens. Digital literacy can be loosely defined as the ability and skill to find, evaluate, utilize, share, and create content using information technologies and the internet [21], and digital culture is promoted by incorporating online technology into citizens' work and lives.

This study aims to provide a better understanding of data-driven smart applications and ascertain the most implemented systems and applications that are in practice globally. It builds on previous research on potential advantages in combining smart and green infrastructure over silo approaches [22] and further investigates how data-driven smart applications can facilitate better services, monitor, and review performances, and improve digital literacy, digital culture, and participation in decision making in future cities. The study acknowledges urban informatics [20] research that examines contexts where new opportunities are created by real-time digital technology and the combination of physical, digital, and social networks and urban infrastructure. It first presents the conceptual background of smart cities, followed by a review of Open Data, Internet of things (IoT), and Big Data technology. How data-driven technologies that produce real time data facilitate smart city functions are explored, followed by a review of their usages, benefits, and advantages. Key challenges and barriers to their mainstream implementations are examined. Smart city indicators (SCI) are reviewed, inferred, and presented with criteria that fall under each category. These criteria are further reviewed for their characteristics and revised, highlighting the benefits, challenges, and impact on quality of life of citizens. Case study data and analysis are presented to illustrate the integrated relationships of SCIs and the probability of their implementation in relation to each other. While there are many case studies that evaluate SCIs in smart city practices [6,23–25], studies that explore the relationship between SCIs to each other are lacking. Hence, this study is unique in its attempt to capture relationships between the SCIs in the implementation and operation processes of smart cities.

2. Research Methodology

Research methodology is qualitative, and data and information are captured from both secondary and primary data sources and different case studies carried out globally. A systematic literature review, including research papers, government and stakeholder reports, case study reports, and action plans, was carried out to obtain an understanding of the current state of the art of smart city practices. This extensive review was further extended to validate the SCIs and identified additional characteristics and factors that could be used to evaluate smart cities.

The PRISMA (2020) and PICO methods were used for keyword searches and the analysis of more than 70 documents, including published reports and industry briefings, in relation to the use of data driven smart applications in city practices. PRISMA [26], the 'Preferred Reporting Items for Systematic reviews and Meta-Analysis', was designed to help systematic transparent literature reviews and report why the review was done, what actions were taken, and what was found, and it includes new reporting guidance to identify, select, appraise, and synthesize studies. Smart cities span across many academic disciplines, and the usage of systematic review is essential [27] to capture all related material. The search focused on published material from major databases such as Business Source Complete (EBSCO), Web of Science, and ABI Inform Global, which are the most relevant for smart city research [28], as well as PubMed, ScienceDirect, and Wiley Online Library. Keywords were selected carefully to capture the recent, most relevant knowledge, and PRISMA played an effective tool in identifying relevant literature sources across multi-disciplinary subjects [29].

The PICO concept uses population/problem, intervention/exposure, comparison, and outcomes to establish the parameters for literature review [30]. It provides a sound basis for formulating the research question and defining keywords for the literature survey from the terms included in the research question. In the PICO approach, a logic grid is constructed (Table 1) for searches using the key terms in the grid. The terms in the logic grid illustrate how the related concepts have been combined to construct a comprehensive search strategy consisting of both keywords/free-text words and index terms [31]. The key terms and synonyms in the logic grid were combined using Boolean operators: 'OR' to combine words/phrases within a column; 'AND' to combine words/phrases in different columns. Accordingly, the search was undertaken across all the selected citation databases with the use of the developed search strategy.

Table 1. Logic grid with identified keywords.

	Population	Intervention	Outcome
Search Terms	Urban city system	Data-driven smart applications	Practices
	Urban system	Smart	Issues
	Urban planning	Smart initiatives	Functionality
	Cities		

In this instance, the following criteria were identified for the literature review:

Population—Urban city system
Intervention—Data-driven smart applications
Comparator—No comparator (an optional element)
Outcome—Current practices/issues

The search strategy included the following keywords: ("urban city system*" OR "urban system*" OR "urban planning" OR Cit*) AND ("data-driven smart application*" OR smart) AND ("practice*" OR "issue*" OR "functionality*") (Table 1).

Examination of case studies [32] allows an in-depth investigation of underlying complex subtleties [33] and is suitable for careful investigation of multilevel units of analysis such as smart cities [34]. A limitation is that literature and information on some case studies are extensive, while the others can be restrictive. This challenge has been overcome by expanding the population and intervention in the PRISMA method. To address the research questions, a qualitative content analysis based on the collected secondary data was performed. Content analysis is used for research studies whose aim is to describe a phenomenon and is usually appropriate when existing theory or research literature on a phenomenon is limited [35]. With this method, the categories emerge from the data rather than using preconceived groupings [36]. Such a qualitative approach contributes to an in-depth analysis of events referred to as multidimensional constructs that are not uniquely measured or defined in existing research, allows to extract from texts (the unit of analysis) fewer content categories, and permits to detect the focal points [37].

3. Conceptual Background and Development of Smart Cities

Contemporary and future cities have to face many critical challenges including climate change, population growth, globalization of economy, risks and ecologies dependencies, technological developments, geo-political changes, human mobility, ageing populations, inequality and social tensions, insecurity (e.g., energy, food, water) and changing institutional and governance frameworks [38]. Existing services and infrastructure systems are mostly outdated and are already stretched to their limits. Global stakeholders are continuously seeking technologically-advanced innovative solutions to face up to the challenges, improve city resilience, and reduce impact on a global scale. This concept of urban resilience addresses the vulnerability of communities in terms of identifying, mitigating, and preparing for risk events and ensuring a rapid recovery after the event has occurred [39]. These risks can be in relation to environment, society and economy, and safeguarding the quality-of-life of citizens and include safety, time and convenience, health, environmental quality, social connectedness and civic participation, jobs, and the cost of living.

Cohen [40] defined smart cities as a broad, integrated approach to improve the efficiency of city operations and the quality of life for its citizens and to grow the local economy. He advocated the real value of smart economy, smart environmental practices, smart governance, smart living, smart mobility, and smart people, citing three key drivers for each goal. The pioneering smart cities wheel presented (Figure 1) included over 100 indicators to help cities track their performance, with specific actions developed for specific needs [41].

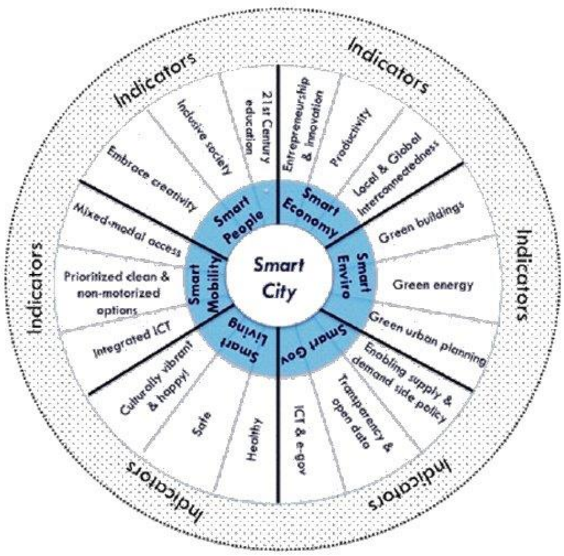

Figure 1. Smart city wheel. Reprinted with permission from ref. [41]. Copyright 2012 Boyd Cohen.

Smart technologies have the capability to face up to urban challenges and are enabling the next wave of public investment [25]. 'Smart' integrates sensors, databases, and wireless access to collaboratively sense, adapt, and provide services for users within the city environment. A comprehensive study focusing on 200 European cities [23] identified several fields of activity that are described in literature in relation to the term 'smart city' as industry, education, participation, technical, and infrastructure. From these fields of activity, the six characteristics that were incorporated in smart cities were identified as smart city indicators (SCI), complementing Cohen's [40,41] work (Figure 2). The study also identified several factors for each characteristic as illustrated below.

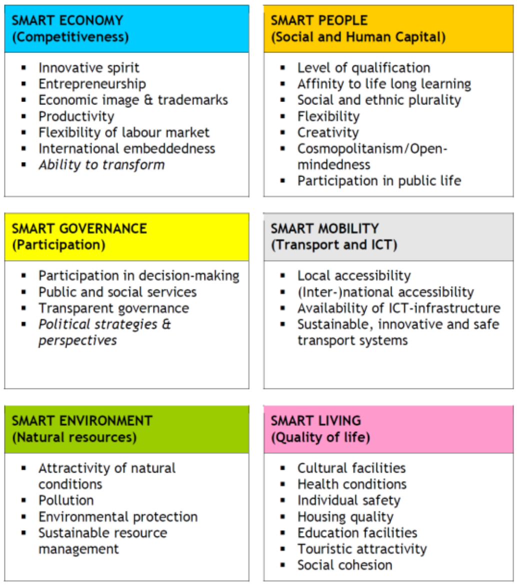

Figure 2. Smart city indicators (SCI): characteristics and factors. Reprinted with permission from ref. [23]. Copyright 2007 SRF-Centre of Regional Science.

Cities, in all their complexities, have the potential to generate vast amounts of data. While there are many definitions, data can be defined as 'characteristics or information, usually numerical, that are collected through observation' [42]. Data usage, data management, and operation are key processes associated with data. Finding the opportunities and insights to innovatively use this data helps governments and authorities to forecast, respond to, and plan for the future. Additionally, access to real-time data and information can provide effective services that improve productivity, resulting in environmental, social, and economic benefits. It also assists in the decision-making processes, informing and empowering stakeholders to make better decisions and choices in shaping and improving the city's overall performance.

Case studies conducted in Europe have now illustrated that embedding ICT and smart systems in urban infrastructure alone will not achieve resilient future cities [24]. While the first examples of smart cities focused only on technology to achieve environmental benefits, the second and current wave of smart cities emphasize the inclusion of socio-economic capital and community engagement. Current trends in smart cities include intelligent, data-driven technology and its applications that can facilitate citizen participation and support decision making and policy formulation. Hence, novel ways of governing that engage stakeholders are emerging and are capable of collecting ideas, anticipating trends, as well as planning and evaluating policy, all in collaboration with citizens.

'Future Cities' is a term used to conceptualize what cities would look like, how they will operate, what systems will orchestrate them, and how they will relate to their stakeholders (citizens, governments, businesses, investors, and others) in the future [38]. Concepts of smart, intelligent, eco, sustainable, and resilient cities are also related to the future cities agenda. Due to increased reliance on innovative technology and communications for delivering basic services, future cities are frequently coupled with smart and intelligent concepts. To be successful, future cities would need to combine integrated social, environmental, and economic aspects with digital, smart, intelligent, networked, and resilient with aesthetically pleasing concepts supported by an overarching governance system. It is recognized that improving digital literacy and digital culture of urban communities forms a key role in achieving these new paradigms of sustainable future cities.

3.1. Open Data, Big Data, and Internet of Things (IoT): Technology That Facilitate Data Driven Applications

Technology, data, and fast connectivity are essential for a smart city to function. Smart technology has the capability to alter the nature, operations, and efficiencies of infrastructure and the capability to provide low-cost solutions for collecting information in relation to usage patterns. With unparalleled volumes of data, local authorities and service providers can find new ways of optimizing existing services. As cities become smarter, the reliance on computer networks and systems increases, and the need to combine this technology with human-centered, responsive solutions that improve the quality of life of citizens becomes crucial.

Cities today generate and act as vast repositories of information and real-time data. When collected and systematically organized, this data can be stored, shared, and applied to provide new ways of services and applications that can influence lifestyles. This capability of cities to collect data via sensors and other smart devices are resulting in large data bases that are difficult to manage and use [43]. Real-time data can be utilized to improve connectivity, information sharing, and performance, resulting in data driven cities and societies. There is a global movement to open up public data and make it more accessible to application innovation, to create novel mobile apps and services, and promote the transparency of governments [43].

Large amounts of publicly available data being continuously generated by many sources, including public and private, are defined as 'Open Data'. This data is stored securely in protective databases or on electronic devices. The nature, variety, and depth of this data is growing as new and increasingly technological solutions are implemented to solve the problems of governments, businesses, and private citizens of smart cities. The potential benefits of data collection on such a scale are immense. Limiting the number of people who can access it limits the number of problems to which it can be applied and, in most cases, prevents access to the people best able to apply it [44]. Several challenges arise at the same time to uphold data security and privacy.

'Big Data' is defined as having volume (ecommerce, mobility, and social media that generate large amounts of data), velocity (generating new data at a rapid pace), and variety (data in many different formats: emails, documents, images, videos, etc.) [45]. Applications that use Big Data sources, incorporating real-time data into computations to direct the measurement process of an application system, are classified as Dynamic Data Driven Application Systems (DDDAS) [46]. DDDAS are vital to operate smart city concepts to combine many infrastructure systems that share portals and feed data into each other's systems to achieve complex joined up performances and results [47].

The 'Internet of Things', or IoT, is a system of interrelated computing devices, mechanical and digital machines, objects, or people that are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction [48]. IoT applications for smart cities include smart homes, smart parking lots, health care systems, water and weather monitoring systems, transportation and vehicular traffic, environmental pollution, and security surveillance systems. Some smart solutions can both respond to demand and involve the public in shaping it [25]. They can be inclusive and personalized to face local challenges and can play a major role in linking people with each other. IoT has the capability to provide long term sustainability solutions in environmental, social, and economic sectors. By installing networks at home, it is possible to manage energy consumption, monitor health situations of the elderly in their house reducing health costs, have surveillance of homes for safety and childcare, and social networking applications that can inform and engage communities at local events.

In an IoT environment, internet links diverse components and devices [49] according to their geographical positions and assess by applying analyzing systems [50]. Smart cities include sensor networks and the connection of intelligent appliances to the internet, which is essential to remotely monitor their treatment such as power usage monitoring to improve the electricity usage, lighting, and air conditioning management. To achieve this aim, sensors can be extended at various locations to gather and analyze data for utilization improvements [51]. Sensor services can be employed in ongoing projects regarding the monitoring of cyclists, vehicles, and parking lots. This data can feed into service applications that utilize an IoT substructure to simplify operations in air, noise pollution control, the movement of cars, as well as surveillance and supervision systems [50]. These concepts not only result in improved livability of cities, but also a more productive place for businesses to operate. There has been a remarkable growth of digital devices, such as sensors, smartphones, and smart appliances, that has complimented commercial objectives of the IoT, as it is possible to interconnect all devices and create communications between them through the Internet.

3.2. Data Driven Smart Applications Usage for City Functions

A city with robust communication networks can rapidly and safely transmit the data collected by smart devices and other sensors. Free Wi-Fi availability in a city is beneficial for visitors as well as residents. Cities are prioritizing faster mobile broadband speeds that are essential to support demanding data usage by citizens. Bandwidth refers to the maximum amount of data that is transferable in each period, and higher band-width applications provide faster connections [52]. Less band-width intensive smart city applications can benefit from low-power wide-area networks (LPWAN), which allow broad deployment of sensors with much lower operating costs [25]. Open Data platforms are another aspect of the data driven technology base and create large volumes of data that can become useful when built into smart applications. In most of these applications, data and connectivity are key in achieving efficient smooth operations. Effective networks and mobile coverage systems, including 4G and 5G, as well as LPWAN connectivity, are crucial in this process and long-term investment in resources are essential to achieve benefits.

In relation to city functions, Big Data and IoT improve operational cost efficiencies, help promote a data driven culture, provide new opportunities for innovation, create new competences and services, accelerate the placement of new services, launch new products and services, increase and provide new sources of revenues, and transform businesses according to future models of operations. Refurbishment and improvement of infrastructure and physical assets are an ideal time to retrofit data driven smart devices. Smart sensors for the detection of conditions and smart meters to accept smart payments are such examples. When city services such as lighting and security are improved, sensors can be introduced to procure installing and maintaining data driven applications. The essential difference between a smart sensor and a standard sensor is its intelligence capabilities [53]. The integrated microprocessor is used for digital processing, analog-to-digital or frequency-to-code conversions, calculations, and interfacing functions, which can facilitate self-diagnostics, self-identification, or decision-making functions [54]. Partnerships with research groups, local organizations, and other stakeholders will improve the local data ecosystem and can help cities manage the technical complexity as well as the funding and analysis needs of applications. These applications will collect citywide data including air quality, noise, weather, and traffic information. A clear data management strategy will provide opportunities to maximize data and collectively co-relate with similar data sets, often from other similar entities or sources. Rather than collecting silo independent data, it is beneficial to collaborate under overarching guidelines to gain cross-departmental insights. Data compatibility from one platform to another is a concern that cities have struggled with for years and can become worse when IoT and Big Data solutions generate masses of new information without a management plan. Developing clear standards for data collection, storage, and sharing can prevent this fragmentation and encourage collaborations and growth.

3.3. Challenges in Using Data-Driven Smart Applications

While there are many benefits to using data driven applications, stakeholders have to face several challenges in operating and managing data. Big Data involves complex technologies in obtaining, storing, and using data concerned with data protection, security, and privacy. The systems could be vulnerable to cross-site scripting (computer security vulnerability found in web applications), hacking, and data leakage. While some countries and sectors are advanced in Big Data and its management, a large majority do not have adequate capacity or knowledge about the technologies and analytical capabilities that are involved. Cities need to adopt serious measures to ensure the privacy and security of citizen's data to avoid data breaches. Without this guarantee, citizens cannot trust the governance systems, and the collection of data and information can be challenging. All systems should be resistant against cyber-attacks, particularly the critical infrastructure and assets that are essential for the functioning of the city. These include heating, water supply, public health, transportation, security services, electricity generation, telecommunication, and financial services. Heterogeneity, reliability, storage and computational ability for large data sets, legal and social aspects that are combined with data usage, and Big Data transfers are the other challenges that are faced by smart city infrastructure networks.

Some of the key challenges are managing the large volume of data and dealing with the continuous data growth, as data needs to be retrieved, stored, and computed. Together with the rise in unstructured data, there has also been a rise in the number of data formats including social media data, audio, video, and smart device data, etc. To maximize the use of complex real-time data that are generated continuously, organizations need to be aware and ready with the necessary tools, capabilities, and insights. Assimilating different data sources and authenticating and securing Big Data are other functions that need to be fulfilled if businesses are to achieve the best results from this data.

Employing and retaining professionals who are skilled in data handling and analysis is another challenge the industry faces, as there is a shortage of skilled personnel with this expertise. This criterion has been cited by many industries pursuing to better utilize Big Data and develop more effective data analysis systems. Training personnel can be costly, and many are working on new areas such as machine learning and artificial intelligence to build insights, but this also takes well-trained staff or the outsourcing of skilled developers [55]. There can also be organizational resistance in adapting to a new kind of working and analysis, and in some cases, cultural challenges remain an impediment to successful business adoption [56]. A survey conducted in 2017, with 1000 senior business and technology decision-makers in USA, found out that 95% of the organizations that participated have undertaken significant investments in Big Data initiatives during the past five years, spanning from $100M to $1B [57] (Figure 3).

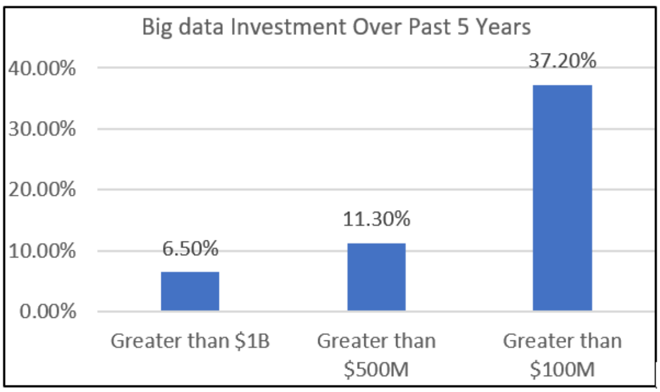

Figure 3. Big Data investment over the past five years [57].

Businesses are working with Big Data, using powerful analytics to drive decision-making, identify opportunities, and boost performance [56]. Data that are collected from a variety of sources can pose potential security problems for cities. There are measures and tools to guard data and analytic processes from attacks, theft, or other malicious activities that could harm or negatively affect them [58]. These data security measures must be introduced from an early stage to collect, store, and retrieve in order to deter any hacking of data that is related to city infrastructure. Cyber-attacks on data storage can cause harm to city service operations and could cause significant monetary consequences such as financial losses, legal actions, or penalties. While none of the Big Data security tools are new, their scalability and the ability to secure multiple types of data in different stages have improved. Encryption, user access control, intrusion detection and prevention, as well as physical security are key factors in this process and relate to the 'cloud'. The 'cloud' refers to servers that are accessed over the internet and the software and databases that run on those servers [59].

4. Smart City Indicators (SCI)

Researchers have adopted six smart city indicators [23] as important and have evaluated and implemented them in many projects [6,24,25,47,50,60].

Smart mobility (SM)—Data-driven applications are used to offer and monitor complex multi-modality systems of transportation to achieve sustainable transport systems that are efficient. Smart parking and smart traffic management techniques that are used to coordinate and integrate different transportation modes are part of smart mobility applications. With the development of Intelligent Transportation Systems (ITS) there are several examples of complex data-driven applications in transportation operations and control [47]. 'Intersection Signal Control' was one of the earliest applications that was implemented in several cities, and since the middle of the last century, traffic controls at many intersections have been driven by real-time data [61]. Embedded vehicle detection on intersection approaches has allowed implementation of control techniques with objectives such as minimizing user travel time, emissions, and energy.

Smart economy (SEcon)—Innovation and productivity are employed to adapt to the market and workers' needs to enhance new resilient global business models for competing both locally and globally. Entrepreneurial innovation hubs where start-ups and business incubators are encouraged also belong in smart economy context. Public and private initiatives that foster the development of new smart projects are an essential part in setting up a comprehensive smart city economic ecosystem. When private sector-initiated innovations spring up, regulating, assembling key actors, offering subsidies, or changing procurement decisions are some of the ways governments can contribute.

Smart governance (SG)—Smart governance can be achieved when citizens and other stakeholders are part of operations in cities, contributing to planning, supporting key decisions, and making processes with the help of smart platforms and applications. The aim is to attain synergies through collaboration and improve public services and the transparency of institutions to promote sustainable communities. Technology helps policy makers to engage, survey, and obtain stakeholder opinions on a range of matters and to incorporate public feedback when improving systems, processes, and policies. To be successful, new initiatives need to be transparent and accountable, engaging citizens from the inception of the project.

Smart environments (SEnv)—Sensors and other innovative monitoring systems can be used to collect data from utility services and networks including energy, air, water, and waste management to provide a more efficient service, conserve energy, and improve the life of citizens while achieving environment sustainability. Big Data can help in the coordination of wind and solar energy with traditional energy sources. Smart sensor data can be processed to find out whether a renewable energy source operates correctly. They can also assist in reducing pollution and promoting biodiversity. The availability of data and new analytical algorithms provide the ability to forecast and obtain a better idea of the impact that climate and environmental changes may have on human health. With this knowledge, the potential natural disasters can be more accurately identified, and cities can become better equipped with warning systems to prevent the harmful impact of environmental factors on citizen's health and well-being.

Smart living (SL)—When public services and facilities are well managed by ICT and data driven technologies to provide a secure, accessible, and healthy lifestyle, smart living concepts can be realized. Smart systems can optimize call centers, first responders to the emergency scenes, and field operations in emergency responses. The response time is critical for emergency responses, and the services have to be linked with traffic system controls, vehicle recognition applications, and speed. Smart living is also concerned with improved health and improved long-term medical treatments and applications that help prevent, treat, and monitor conditions. Remote patient monitoring systems, which take a proactive and preventive approach to treatment, have the potential to reduce the health burden on economy by more than 4% [25]. These networked systems securely transmit vital readings to health professionals in other locations for assessment, which can inform and alert both the patient and the medical team when early intervention is needed, reducing complications and the need for hospitalization.

Smart people (SP)—Data-driven smart applications resulting in inclusive communities, opportunities for education, digital literacy, and access to digital platforms all contribute to the smart people agenda and include neighborhoods with free Wi-Fi, renewable energy powered utility services, and new housing with intelligent systems. Smart cities also raise questions of equity [25] and bringing citizens online making them digital literate becomes a priority, as most data-driven applications require smartphones or smart equipment. Aging populations can benefit from this type of application, where patients are monitored remotely to detect and treat early to avoid hospitalizations and help seniors live independently. In implementing smart people criteria, the requirements of each neighborhood and community vary and should be considered autonomously to promote digital culture and participation.

Evaluating Smart City Practices

A comprehensive literature review in relation to smart city practices resulted in identifying further criteria that fall under the SCIs, which can be used to carry out a wide-ranging evaluation covering environmental, social and economic aspects that can be significant for all city stakeholders. Figure 4 presents these revised criteria under each of the smart city indicators.

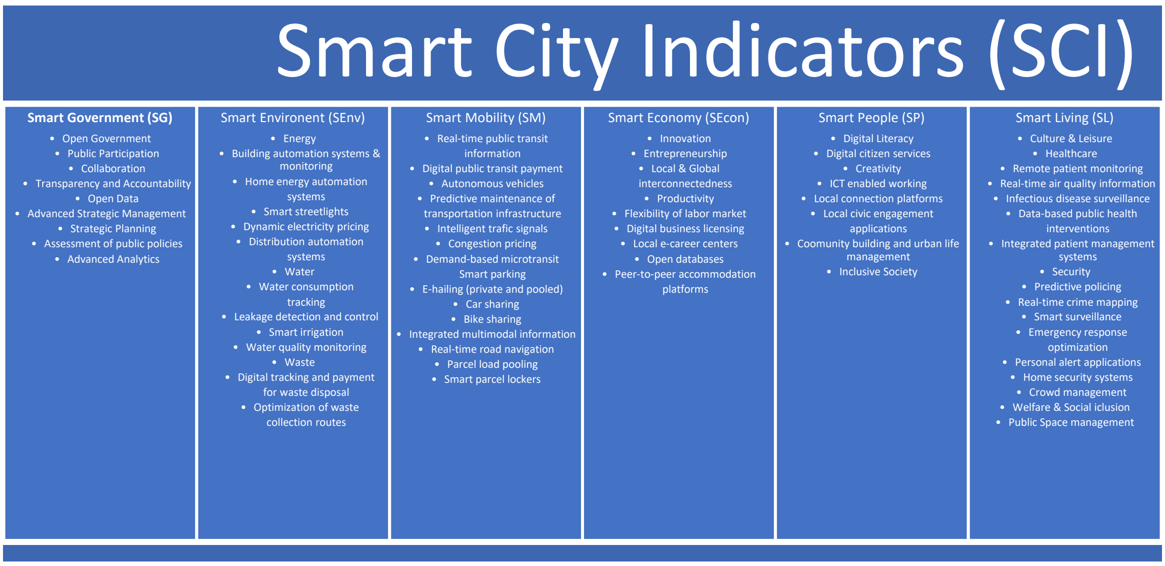

Figure 4. Smart city indicators with revised evaluation criteria for the study.

Case studies provide a detailed understanding of a single or several cases set in their context [62]. Case studies are also viewed as a useful tool for the initial and investigative stages of new research areas [63]. Case study analysis as well as theoretical understanding of the phenomenon under study in related literature assisted in the review and evaluation of this study. For the evaluation of smart city practices, qualitative analysis was carried out by an inductive approach that examined key words and phrases within the case study review literature and resulted in identifying relationships and criteria that were common or distinctive in the example studies.

A sample of 50 case studies that use data driven applications deployed in real-world settings were identified from literature and appraised according to the SCIs and the related criteria presented in Figure 4. Content analysis identified key words and phrases that can be apportioned to each SCI and formed the qualitative data for the analysis. The analysis investigated which indicators were frequently implemented, their relationship, and the probability of SCIs being integrated with each other. Appendix A, Table A1 presents key words and phrases that were captured regarding the use of smart applications in relation to the key SCIs that were identified. The data illustrate that the majority of smart cities use data driven applications in all categories to improve operations and achieve efficiency. Smart mobility, smart living, smart environments, and smart economy criteria are implemented quite commonly, while smart governance criteria are relatively new to be implemented (Figure 5). It can also be seen that these systems are integrated and rely on each other for the efficient functioning of cities.

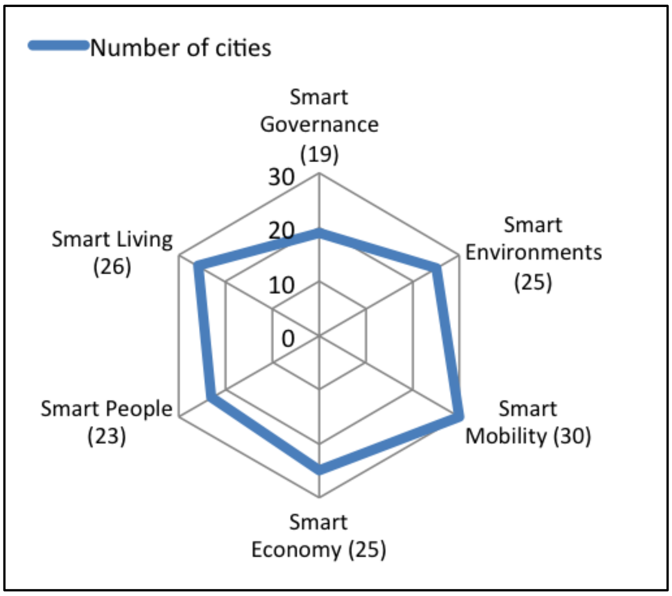

Figure 5. Usage of data driven smart city applications according to smart city indicators and evaluation criteria.

Smart mobility and transport concepts have been implemented in cities for some time [25] and cover a wide range of criteria. From the 50 cities surveyed, DDDAS smart transportation systems management and control functions were employed in 30 cities. In the sample, a variety of data-driven traffic control systems have been implemented for the efficient performance of city services and include interactive notifications of parking availability and distribution, autonomous vehicles, bike, car, and ride sharing, congestion pricing, digital public transit payment, predictive maintenance of transportation infrastructure, real-time public transit information, and road navigation and mobility aspects [64]. These applications support agent-based simulations of transport systems and many encounters they can face so that complex systems that incorporate and respond to a multitude of entities, including the shortest routes, minimal waiting times, and diversions away from traffic congestions, can provide the optimum traffic solutions. The new vehicle connected technology is allowing the vehicles to self-identify themselves in the system, and this ability creates important new opportunities in scheduling arrivals at destinations, providing user-specific trajectory guidance to minimize energy and emissions, and real-time routing [47].

Smart economies support entrepreneurship and a culture of innovation, and 25 cities in the sample were implementing data-driven smart economic concepts embracing an open approach to support innovation and providing opportunities for entrepreneurs. Most cities have initiated programs to support business ideas and start-ups and initiatives such as the 'Global entrepreneurship week', the 'Innovation week', and the 'Start-up weekend' [6]. An emerging trend is also to initiate innovation hubs. Smart economy examples present in the sample are public-private partnerships that bring together municipal agencies, educational institutions, non-profit agencies, private-sector companies, and start-ups that put people at the center and use technology to unite the city. Several smart economic approaches present are based on the close collaborations between academia and businesses in the innovative technology specialization sectors.

In data driven smart cities, Big Data and analytics help utilities providers to gain operational efficiencies in smart environments [65]. Organizations and citizens consider how to maximize the use of resources while preserving them, and 25 case study examples were utilizing smart environment techniques. In the sample, the utility management sector has witnessed the rise of 'smart': smart grids, smart water and energy meters that reduce waste and increase efficiency with the help of technology. The fast distribution of smart grids has enabled the generation and analysis of real-time power generation and consumption data. The energy use habits of residents and industries have helped to predict the need for future energy supplies, and smart grids can redirect electricity from surplus areas to where it is needed.

Data Driven Application Systems (DDAS) that provide digital platforms and promote digital literacy in citizens to engage in digital services come under smart people city services, and 23 examples were identified in the case study sample. Many government departments and authorities have added new digital infrastructure, new roles, and personnel to support digital services to promote people using smart networks. Establishing data science teams and analytic units distributed in all sections of the government to support these services are essential in this effort. Living laboratories and pilots have provided the opportunity to test applications and overcome any problems that are identified. In the study sample, all related stakeholders benefit with the freedom to make bolder decisions, to experiment, learn, and recalibrate application according to feedback.

City governance can be influenced by technology and by changing the relationship between the local authorities and citizens. In the case study examples, 19 cities were using smart governance systems. With the aid of data-driven digital platforms, citizens can engage in dialogue with local authority officials and agencies via interactive mobile apps and social media platforms. While there are several early examples where technology has alienated people (Masdar City- Abu Dhabi, Songdo- South Korea), in recent cases it is effectively used to build real-world communities and personal connections via social networks to promote volunteering, mentoring, and community engagement. This can be more relevant in local contexts where citizens can have a direct influence on the decision-making processes related to their communities.

From the 50 cities surveyed, 26 cities were implementing criteria listed under smart living. While improving security and health, DDAS technologies can improve the quality of life of citizens by facilitating engagement in culture and arts and include online information sharing, ticketing, and reservations. In the sample, smart security measures implemented include real-time crime mapping that utilizes data and statistical analysis to highlight potential conflict areas and patterns and predictive policing that could anticipate crime to prevent incidents before they occur. Other measures present included promoting culture and leisure activities and health and security monitoring by smart systems.

A statistical heatmap (Figure 6) shows the percentage of cities that employed various SCIs together using conditional probability. By considering a particular SCI on the x-axis, the y-axis shows the percentage of cities in the study that also implemented the other SCI alongside. This type of analysis can help to develop greater understanding of which SCIs work better together, which are more applicable in a silo capacity, and even to suggest in what order SCIs are being implemented in cities. Smart people (SP) criteria seem to be the most integrated with other SCIs, indicating that SP was often found alongside the other SCIs. Firstly, this suggests that SP might not be particularly effective when implemented alone and needs to be supported by other SCIs to be fully effective. Moreover, it could also suggest that SP is implemented last in a city's smart development. This would probably be because smart application infrastructure and support need be laid first for individuals to buy in to the smart concept and applications. On the contrary, smart economy is showing that it has often been implemented in a silo fashion, also suggesting that it could be a starting point for a city's smart development.

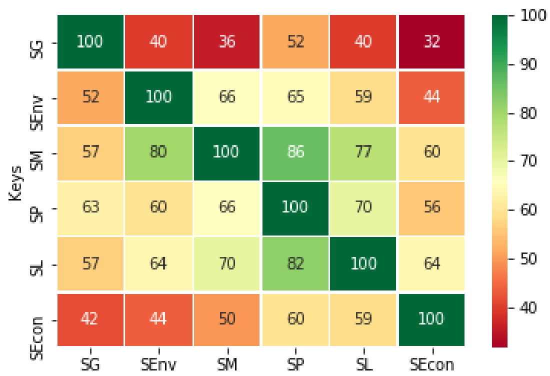

Figure 6. Statistical heatmap depicting the relationships between SCIs pertaining to the case studies.

The data suggest that smart mobility and smart people have the strongest integration with other SCIs, followed by smart people and smart living. Smart economy has the least integration, whilst smart governance has a low-level of implementation, meaning it was not a commonly-used policy in this case study sample. Figure 7 highlights the stark difference in the integration between smart people and smart economy, showing how SP is more likely to be implemented alongside each of the remaining SCIs than smart economy. The results of the study illustrate that human-centered policies are fundamental to the current and future development of smart cities, but these methods are often implemented later in the development process after other technology has been successfully embedded into the city.

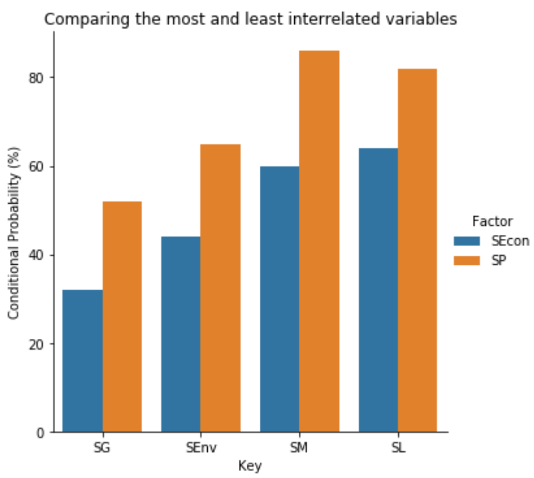

Figure 7. Comparison of the most and least interrelated variables.

Urban informatics theories help in exploring the intersection of notions, trends, and considerations for technology, place, and people in urban environments [20], as represented by SCI that are integrated at many levels. These trends, and the accelerated crisis in environmental, economic, and social sustainability, inform the future role of community engagement in contributing to enhancing urban sustainability. The complexities, trends, and considerations in cities require real-time examination to understand both tangible and intangible elements of the city. De Souza e Silva [66] identified this quality of city as a 'hybrid space' between the social, physical, and digital networks and infrastructure.

In the literature and analysis, a number of trends that contribute to new paradigms of future cities can be identified: digital technology is becoming more common, accessible, and embedded in everyday life; easily accessible real-time information due to the deployment of sensor networks, media, and mobile devices; the potential and opportunities provided by the real-time mobile information systems that have wide-ranging impacts in removing barriers to behavioral changes of citizens [67]; finally, the accessibility and availability of related tools that can be used by community stakeholders to engage and inform city planning and decision making.

These trends have provided the context for a new urban planning and decision-making regime where citizens can become involved in enhancing sustainability through active civic engagement, meaning participatory culture is no longer limited to the technically skilled or the civically inclined [68,69] and has the potential for a new cultural citizenship, where citizen engagement in the decision making is becoming more and more possible (Figure 8). This participation can lead to greater social inclusion, fairer access to and smart use of information and services, urban sustainability, and healthier local economies [20]. Understanding the opportunities provided by data-driven applications and the real-time data they generate will assist in facing the climate change challenges and behavioral changes that are necessary in facing these challenges.

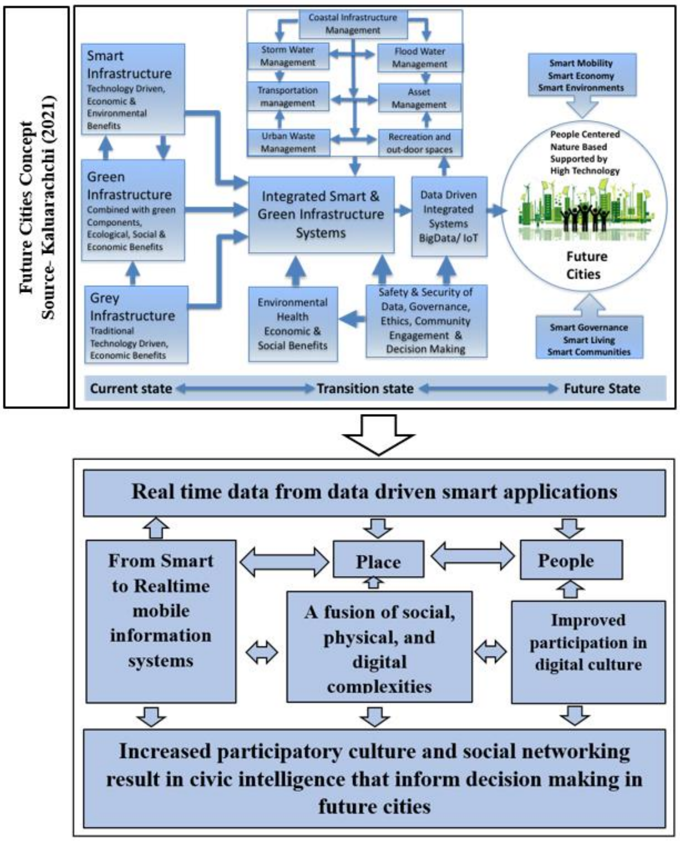

Figure 8. Real-time data promoting participatory culture.

5. Conclusions

Future cities can greatly benefit by adopting data-driven applications to achieve performance efficiencies, mitigate climate effects, as well as improve the quality of life of citizens. Big Data can promote innovations, create new paradigms and workplaces, and improve the biodiversity of the environment. There has been considerable progress in data-driven application usage to perform and monitor city functions in recent years, as the ever-present challenges of connected societies continue to grow. The importance of being digitally literal, being connected to online services, and having access to real-time data has been further exacerbated in the current pandemic where many essential activities are carried out remotely via digital online methods.

Data-driven smart applications enable better governance and operational implementation by the capability to improve public participation. They can help nurture innovation, promote sharing of information, and engage communities to improve the performance of the city. To take full advantage of IoT, cities must integrate it into existing data strategies while addressing new challenges and continually refining their procedures. When working with Big Data, security and privacy issues are critical to address. All parties who are involved with gathering, storing, and analyzing data must take the necessary steps to safeguard and ensure that data is protected and that the understanding with any other party in relation to data usage is clear. Transparency on what data is stored and how, who can access it and to what extent, and the actions taken to protect sensitive data are essential to show citizens that their information is being handled correctly and ethically.

The study results illustrate that smart people, smart living, and smart governance criteria are integrated and play an important role as smart mobility, smart environments, and smart economy. Smart mobility is the most widely implemented technological aspect that has been in place for the last two decades, whilst smart governance, a relatively new phenomenon, can also be seen in some cases, particularly in the developing world where technological implementation is difficult due to resource limitations. This demonstrates that even though some cities have not received highly technical infrastructures, they are still opening to new, transparent, and participatory governance approaches where citizens play a key role. The study results suggest stark difference in the SCIs with regards to their implementation as either silo methods or as part of a diverse smart package. The development of smart people, smart living, and smart governance concepts illustrate that the current new wave of smart cities is realizing the importance of human and social capital in future cities. There is demand for improved health and well-being of citizens and a more sustainable work–life balance that advocates eco-friendly healthy cities. These shifting paradigms give insights to policy makers, urban planners, and designers in prioritizing resources and implementing future city strategies.

Access to real-time data can result in digital literacy and digital culture that improve public participation, online deliberation systems, and societies of urban futures. Social networking, collective and civic intelligence, and crowdsourcing are the way forward for urban futures coupled with the rise of technologies, such as wireless internet and mobile applications, and the impact of neogeography, simulations, and 3D virtual environments that reproduce and analyze complex social phenomena and city. Data-driven smart cities are places where entrepreneurs can innovate, and technology can contribute to improve the quality of life, security, protection of nature, and the way forward for future cities.

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Appendix A

Table A1. Global smart city applications, categorized according to the smart city indicators.

City, Country	Key Data Driven Smart City Applications	Main Key SCI
Amsterdam, The Netherlands	Citizen participation, smart lighting controls for energy efficiency and saving, improved safety, traffic reduction, digital platforms for citizens, and Open Databases	SG, SEnv, SM, SP, SL
Groening, The Netherlands	Energy efficient systems and real-time transportation information	SEnv, SM
Nice, France	Smart applications for lighting, road circulation, waste management, and environment monitoring	SEnv, SM, SL
Padova, Italy	Environmental monitoring via smart sensors	SEnv
Turin, Italy	Digital portal with services and information for citizens, user-centric design accessible to all public information and services, and smart meters	SG, SEnv, SP
Barcelona, Spain	Combined information, communication and green technologies, smart water efficiency, smart public transportation, participatory democracy, Open databases, and smart entrepreneur opportunities	SG, SEnv, SM, SEcon, SP, SL
Bilbao, Spain	Citizens participating in the neighborhood decision making, smart parking systems, data platforms, and Open Data systems	SG, SM, SP
Santander, Spain	Citizen participation, smart parking systems, and digital literacy platforms	SG, SM, SP
Stockholm, Sweden	Fiber optic communication network and wireless infrastructure for market growth	SEcon, SL
Malmo, Sweden	'Citizen centric' portals, citizens at the center of decision making, and data platforms	SG, SL
Copenhagen, Denmark	Citizen participation, tech base, fast broadband and mobile connections, smart energy incubators and energy labs aims to become carbon-free by 2025, smart transport systems, and Open Data platforms	SG, SEnv, SM, SEcon, SP, SL
Brno, Czech Republic	Promotion and support of entrepreneurship	SEcon
Plan IT Valley, Portugal	Introduction of sensors for monitoring	SEnv
Porto, Portugal	Porto innovation hub	SEcon
Norfolk, UK	Local authority using data driven applications and environmental monitoring	SG, SEnv
London, UK	Citizen participation, green and smart technology application in transport and parking, pollution and congestion control, innovation in entrepreneurship, digital platforms for citizens, and Open databases	SG, SEnv, SM, SEcon, SP, SL
Liège, Belgium	VENTURELAB for innovation	SEcon
Vienna, Austria	Energy efficiency via smart sensors, smart mobility systems	SEnv, SM
Friedrichshafen, Germany	GPS individual distress signaling, mobile remote health monitoring, smart metering, smart transport systems, and Open data platforms	SEnv, SM, SEcon, SP, SL
Busan, Korea	Cloud infrastructure connecting shared applications, geographic information and intelligent transportation, digital platforms, and Open Data systems	SM, SEcon, SP, SL

Table A1. *Cont.*

City, Country	Key Data Driven Smart City Applications	Main Key SCI
Songdo, Korea	Energy efficiency, digital connectedness, high surveillance, waste management, fully automated buildings, and smart street lighting and meters	SEnv, SM, SEcon, SP, SL
Pune, India	Open data portal to support evidence-based policy making, environmental sensors, and extensive public Wi-Fi network.	SG, SEcon, SM, SP, SL
Dholera, India	Smart infrastructure that integrates transit networks, logistics hubs	SM, SEcon
Fujisawa, Japan	Reduction of carbon emissions, smart mobility management	SEnv, SM
Shanghai, China	Crowd movement control, intelligent urban infrastructure, and digital platforms	SM, SP, SL
Beijing, China	Intelligent urban infrastructure, sharing data and public services for healthcare and education among cities, and digital platforms	SM, SP, SL
Singapore, Asia	Energy efficiency, transportation, home and environment, business productivity, healthcare, and public sector services	SEnv, SM, SEcon, SP, SL
New York, NY, USA	Digital tools to share information to overcome crime and innovation in entrepreneurship	SEcon, SP, SL
Chicago, IL, USA	Digital tools to share information to overcome crime and innovation in entrepreneurship	SEcon, SP, SL
Santa Cruz, CA, USA	Predicting the policing of areas, smart mobility management	SM, SL
Phoenix, Arizona, USA	High-speed networks and sensors, streets and traffic signals designed to accommodate autonomous vehicles	SEnv, SM
San Francisco, CA, USA	Citizen participation, conservation of water, replacing areas of non-native plant life with native, drought-resistant flora, interconnected smart streetlights system	SG, SEnv, SM, SEcon, SP, SL
Seattle, WA, USA	Digital government portal with language support, Open Data and open government, IT cloud, equitable justice delivery system, communities online, smart grid, and digital evidence management	SG, SEnv, SM, SEcon, SP, SL
Quebec City, QC, Canada	Open Wi-Fi, infrastructure management system, Open Data initiative: making city data open, and online transportation control system	SEnv, SM, SP, SL
Toronto, OH, Canada	Integrated mobility, minimized energy consumption, waste and emissions, and garbage robots that transport waste in underground tunnels	SG, SEnv, SM, SP, SL
Vancouver, BC, Canada	Integrated mobility, green city concepts, and energy saving options	SEnv, SM, SP
Brisbane, Australia	Smart infrastructure, economic growth and environment sustainability, and community involvement in urban city decisions	SG, SEnv, SM, SEcon, SP, SL
Neom, Saudi Arabia	Usage of renewable technology and robotics, crowd control	SEnv, SL
Masdar City, UAE	Smart living and office spaces, clean-tech innovation clusters, use of renewable energy and low carbon buildings, and digital platforms	SEnv, SM, SL, SEcon, SP
Moscow, Russia	Intelligent transport systems, cloud platforms	SM, SL
Rio de Janeiro, Brazil	Citizen participation and transparency, crime mapping systems,	SG, SL
São Paulo, Brazil	MOBLAB+ space, an open innovation laboratory for the development of solutions, innovation in mobility	SEcon, SM

Table A1. *Cont.*

City, Country	Key Data Driven Smart City Applications	Main Key SCI
Medellin, Colombia	Citizen participation in allocating city budgets, financing for innovation	SG, SEcon
Santiago, Chile	Smart meters, entrepreneurship, smart mobility and traffic management, and applications in healthcare	SEnv, SM, SEcon, SL
Villa Gesell, Argentina	'Citizen centric' portals where citizens are at the center of decision making	SG
Guatemala, Central America	'Citizen centric' portals where citizens are at the center of decision making	SG
Quito, Ecuador	Services to assist and support entrepreneurship	SEcon
San Miguel de Ibarra, Ecuador	Pre-incubation, incubation, and acceleration programs with enterprises	SEcon
Tequila, Mexico	Services to assist and support entrepreneurship	SEcon
Carthage, Tunisia	Portal on budget distributions containing data in an open format, allowing the visualization and distribution of data	SG

Key for SCI: Smart governance—SG, Smart environments—SEnv, Smart mobility—SM, Smart economy—SEcon, Smart people—SP, Smart living—SL.

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