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Enhancing sustainable urban development through smart city applications

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Abstract

Purpose – This paper investigates the potential contribution of smart city approaches and tools to sustainable urban development in the environment domain. Recent research has highlighted the need to explore the relation of smart and sustainable cities more systematically, focusing on practical applications that could enable a deeper understanding of the included domains, typologies and design concepts, and this paper aims to address this research gap. At the same time, it tries to identify whether these applications could contribute to the "zero vision" strategy, an extremely ambitious challenge within the field of smart cities.

Design/methodology/approach – This objective is pursued through an in-depth investigation of available open source and proprietary smart city applications related to environmental sustainability in urban environments. A total of 32 applications were detected through the Intelligent/Smart Cities Open Source (ICOS) community, a meta-repository for smart cities solutions. The applications are analyzed comparatively regarding (i) the environmental issue addressed, (ii) the associated mitigation strategies, (iii) the included innovation mechanism, (iv) the role of information and communication technologies and (v) the overall outcome.

Findings – The findings suggest that the smart and sustainable city landscape is extremely fragmented both on the policy and the technical levels. There is a host of unexplored opportunities toward smart sustainable development, many of which are still unknown. Similar findings are reached for all categories of environmental challenges in cities. Research limitations pertain to the analysis of a relatively small number of applications. The results can be used to inform policy making toward becoming more proactive and impactful both locally and globally. Given that smart city application market niches are also identified, they are also of special interest to developers, user communities and digital entrepreneurs.

Originality/value – The value added by this paper is two-fold. At the theoretical level, it offers a neat conceptual bridge between smart and sustainable cities debate. At the practical level, it identifies under-researched and under-exploited fields of smart city applications that could be opportunities to attain the "zero vision" objective.

Keywords Urban sustainability, Sustainable development, Smart cities, Technology-led development, Urban innovation, Zero vision

Paper type Research paper

1. Introduction

Sustainable urban development and smart cities represent two growth paradigms that emerged in the previous century as a result of the drive of cities to be more responsive to citizen needs, offer conditions that promote high quality of life and sustain and enhance competitiveness in an increasingly globalized environment. The realization that unsustainable consumption of resources brings humanity closer to a future where basic goods will be unavailable to large parts of the population, coupled with significant

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technological advancements in reducing resource consumption, monitoring urban environments and making informed technical and policy decisions, is bringing the two disciplines closer than ever before, despite the different growth trajectories followed until recently.

Recent research and policy reports indeed highlight synergies and benefits at the intersection of sustainable and smart urban development. It is characteristic that the most recent and widely cited report of the World Urbanization Prospects series of the United Nations (United Nations, 2014) not only documents a consistent global urbanization trend in the past, but it also clearly states that this trend will continue to rise at least up to 2050. Most importantly, it calls for integrated policies to improve urban and rural living conditions and highlights the role of technology in mitigating the rising sustainability challenges. As mentioned in the report, the policy implications rising from this study include – among others – the necessity to have accurate, consistent and timely data to inform city-related policy-making, as well as the usage of information and communication technologies (ICTs) toward facilitating a sustainable mode of urbanization, one that enhances and efficiently delivers services to urban stakeholders. The United Nations have already begun action-oriented research in this direction, by exploring the role of big data for sustainable development (United Nations, 2015a).

The European Union's (EU) policies also highlight the synergy between smart technologies and sustainable urban development. With Europe 2020, the EU's current 10-year growth strategy, the objectives of fostering a smart, inclusive and sustainable growth in Europe were set. Innovation lies at the heart of the strategy, and is seen as a means to tackle challenges, inclusive of climate change and energy efficiency. Moreover, through the Smart Cities and Communities European Innovation Partnership, launched by the European Commission (EC) in 2012, the energy, transport and ICT industries are invited to work together with cities to address the cities' needs. This will enable innovative, integrated and efficient technologies to roll out and enter the market more smoothly, making cities the nexus of innovation (European Commission, 2012). The pertinence of the smart city concept with the one of environmental sustainability is also reflected in the EU's regional and urban development policy, whereby greener technology is seen as an asset toward reducing greenhouse gas emissions and fostering urban collective intelligence and innovation (European Commission, 2011).

Despite the aforementioned policy developments, Ahvenniemi *et al.* (2017) report that there is a misalignment between the targets of smart and sustainable urban development assessment frameworks, with smart city frameworks downplaying the importance of environmental sustainability. The authors propose a redefinition of the smart city concept toward a more integrated direction – one that highlights the environmental sustainability dimension. Salvati *et al.* (2013) also note that the contribution of smart cities to sustainable development remains vague. Hilty *et al.* (2011) focus on the crucial role that ICTs could play in sustainable urban development, exploring how it could be used to decouple resource consumption and environmental impact from economic growth. They note, however, that the topic of "ICT for sustainability" has not attracted actionable political interest as of yet. Other recent work in the specific field of smart sustainable cities highlights the need to explore the relationship between the two more deeply (Bifulco *et al.*, 2016). Even more significantly, a recent interdisciplinary review of the scientific literature at the intersection of smart and sustainable cities revealed that very few studies have been published in mainstream journals on the topic. Among others, a necessity to study smart (and) sustainable cities by means of practical applications emerges. It would enable a deeper

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understanding of the included domains, typologies and design concepts (Bibri and Krogstie, 2017).

This paper is largely inspired by the above developments in the sustainable and smart urban development domains. Addressing the aforementioned policy and theory gaps, it investigates the potential contribution of smart city approaches and tools to sustainable urban development. This objective is pursued through an in-depth investigation of the characteristics of 32 open source and proprietary smart city applications related to environmental sustainability in urban environments. The results can be used to inform policy toward more proactive, integrated and impactful directions, both locally and globally. They are also of interest to developers and their communities, as well as entrepreneurs active in the smart city applications domain, as they identify unaddressed market niches.

The structure of this paper is as follows. In Section 2, we introduce and explore the three concepts of "sustainable urban development", "smart cities" and "sustainable smart cities". The focus is both on presenting those concepts, and on exposing underlying needs and weaknesses of the smart and the sustainable city, allowing for a deeper understanding of the value and potential synergies between them. Section 3 presents the design of the research, namely, the objective, the method pursued and the cases included in our study. Section 4 describes the findings of the research both individually, grouping the applications according to the environmental challenge they address, and comparatively, analyzing the research components across all applications. Building upon the research findings, Section 5 proceeds with policy recommendations toward advancing technology-driven innovation for urban sustainability. It also offers research and development recommendations toward scoring a better match between sustainability-driven smart city tools with current needs and demand.

2. Current research at the intersection of sustainable urban development and smart cities

2.1 Sustainable urban development

Sustainability is a new development paradigm that emerged from thinking at the intersection of the environmental, social and economic concerns of the late twentieth and early twenty-first century. There is no widely accepted or canonical definition of sustainability, with sustainable development being a contested concept (Molnar *et al.*, 2001). Although concerns about the limits to growth (Meadows *et al.*, 1972) had first appeared about 15 years before, the discussion about sustainability became popular after the 1987 Brundtland Commission, whereby sustainable development was defined as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). In the following years, sustainable development came to the fore of scientific interest and policy-making, with international organizations' – especially the United Nations – creating related programs, reports and conferences (Atkinson, 2007).

The central role of cities in sustainable development is clearly reflected in the Sustainable Development Goals (SGDs) of the United Nations (2015c) 2030 Agenda for Sustainable Development, which is to "make cities and human settlements inclusive, safe, resilient and sustainable" (SDG Goal 11). The defining role of cities in sustainable global and local development is now well documented (European Commission, 2011; United Nations, 2015c). In cities, vast amounts of energy are consumed in domains such as heating and cooling of buildings; infrastructure building and maintenance; public service provision in transport, public lighting and waste management, to name a few. Inevitably, contemporary cities – because of the large accumulation of people and activities – are the world's major environmental polluters and energy consumers. The consequences of inaction against the

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current situation would be detrimental, especially in the areas of water management, accessibility and urban air pollution (Organization for Economic Co-Operation and Development, 2012).

As a result, the concept of sustainable urban development emerged, and largely penetrated urban planning and development starting at the early 1990s (Bibri and Krogstie, 2017). A city (and any ecosystem) is thought to be sustainable "if its conditions of production do not destroy over time the conditions of its reproduction" (Castells, 2000). Sustainable development is essentially a form of intergenerational solidarity, whereby older generations consciously consume and pollute less, so that future generations will be able to enjoy the same or even better living conditions (Castells, 2000). The desired outcome is a state where cities are more livable, wealthier than before, consume less resources and minimize the environmental impact of human activity (Bibri and Krogstie, 2017).

The penetration of sustainable urban development practices in urban planning and development is so large that in recent years we have seen a vast array of technical and environmental performance requirements appearing both on the building and the neighborhood scale. The increasing number of mainstream sustainable urban development assessment frameworks includes indicator and requirement systems such as LEED for Neighborhood Development, CASBEE for Urban Development, EarthCraft Communities and BREEAM Communities. Comparative assessments among them are provided by Sharifi and Murayama (2013), Haapio (2012) and Nguyen and Altan (2011). The findings most pertinent to our research from those assessments are the ones of Haapio (2012). The author, through a comparison across three commonly used sustainable development assessment frameworks, found that the "infrastructure" category is the most significant one (35 per cent of the framework criteria), followed by "ecology" (20 per cent), "resources and energy" (16 per cent) and transportation (14 per cent). Other categories occupy smaller portions. Essentially this means that the adequacy, quality and resource efficiency of urban infrastructure may be regarded as the most important and defining characteristic of sustainable communities at present.

Speaking of urbanity, cities offer ideal testing grounds for new solutions. They are essentially places where new ideas are created, tested and advanced. Thus, many approaches and sustainable urban development frameworks reference the role of ICTs and citizen participation in advancing sustainability goals in cities (Angelidou and Psaltoglou, 2017; Taghavi *et al.*, 2014). For example, the UN's 2030 Agenda for Sustainable Development sees technology and ICT as a means to achieve human progress and knowledge in societies, promote economic development and protect the environment, increase resource efficiency, upgrade legacy infrastructure and retrofit industries based on sustainable design principles (United Nations, 2015b, 2015c). The great and multifaceted potential of the smart city approach has already been an issue of investigation for the United Nations (2015a), through their study on "Big Data and the 2030 Agenda for Sustainable Development".

2.2 Smart cities

Smart cities represent a conceptual urban development model driven by the conceptual and process innovations of the twentieth century and enabled by the tremendous technological advancements of the past 35 years (Angelidou, 2015; Komninos, 2011). In the current smart city research and practice, technology is regarded as an enabling force for the emergence of new forms of intelligence and collaboration that together enhance the problem-solving capacity of the city. The penetration of the smart city concept in policy-making in recent years has been impressive. It is difficult to provide specific numbers because of the different definitions and approaches used: for example, a recent corporate market report identified about 250 smart city projects worldwide (Navigant Research, 2017); another report speaks of 240 smart cities with populations over 100,000 in Europe (Euractiv, 2017); and India alone is in the process of developing some 100 smart cities (Government of India, 2017).

One of the major challenges with regards to the concept of the smart city is its "self-congratulatory" nature (Hollands, 2008), with "smart city" often acting more as a "label" (Glasmeier and Nebiolo, 2016; Van Den Bergh and Viaene, 2015), rather than actually representing empowerment and intelligence infusion across a variety of stakeholders and sectors of the city. The idea is highly contested, and there is conceptual ambiguity with regards to what it means to be a "smart city" or which methods should be used by a city that wants to become "smart" (Glasmeier and Nebiolo, 2016; Hollands, 2008; Komninos, 2011; Lombardi *et al.*, 2012; Nam and Pardo, 2011; Vanolo, 2014). This is a result of the different ideological roots and conceptual variations behind the idea (Fernández-Vázquez and López-Forniés, 2017; Kitchin, 2015; Pierce and Andersson, 2017), the lack of performance metrics that could justify replication of best practices (Glasmeier and Nebiolo, 2016; Marsal-Llacuna *et al.*, 2015) and the diffusion of market push-driven solutions originating in industry (Angelidou, 2015; Glasmeier and Nebiolo, 2016; Söderström *et al.*, 2014). These challenges raise very practical questions about the smart city. For example, can a city that implements a smart mobility system be regarded as a smart one? Or, can a top down smart city solution imposed without public consultation in a city actually make citizens act in more intelligent ways? In recent years, there has been a very extensive discussion in the smart city domain in respect to the previous points (Angelidou, 2017a, 2017b).

Integrated approaches for the smart city focus on creating an enabling environment, where human capabilities are nurtured through prompt and real-time technology and information, allowing for the emergence of advanced forms of urban intelligence in an environment of responsiveness and flexibility (Datta, 2015; Greenfield, 2013; Lind, 2012; Marsal-Llacuna *et al.*, 2015; Townsend, 2013, Visvizi *et al.*, 2017). In such approaches, spatial intelligence is manifested through the advancement of a city's problem-solving capacity by using its intellectual capital, innovation institutions and physical space more effectively. Advancements in these three areas enable three corresponding types of intelligence: the inventiveness, creativity and intellectual capital of the city's population; the collective intelligence of the city's institutions and social capital; and the artificial intelligence of public and city-wide smart infrastructure, virtual environments and intelligent agents (Komninos, 2015, 2008). Building upon this spatially enabled intellectual capacity, cities and communities can address more effectively pressures related with competitiveness, sustainability and social inclusion – both in the present and in the future (Angelidou, 2014; Angelidou *et al.*, 2012; Deakin, 2011; Komninos, 2011). Moreover, on the international policy level, environmental sustainability objectives are regarded as an inextricable component of the smart city (European Commission, 2012; United Nations, 2015b).

That said, from the early years of the popularization of the smart city concept, a considerable number of the available definitions for the smart city have included the objective of sustainability (Caragliu *et al.*, 2011; Giffinger *et al.*, 2007; Schaffers *et al.*, 2012; Wolfram, 2012) and reference "smart environment", "smart energy", "smart utilities", "smart water" and other environment-related domains as integral to the smart city (Cohen, 2012; Giffinger *et al.*, 2007; International Telecommunications Union, 2014; Komninos, 2011; Lombardi *et al.*, 2012; Zubizarreta *et al.*, 2015). This broad "smart environment" category refers to the ability of smart city tools and applications to improve the environmental performance of cities by introducing environentally friendly technologies, enabling a more accurate monitoring of how urban resources are consumed and a monitoring of the proper function of urban infrastructure. Marsal-Llacuna *et al.* (2015) actually identify the origins of

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the smart city in environmentally friendly and livable cities. They explain that because of this orgin, smart cities encompass sustainable development and quality of life principles, which in turn are enhanced by modern and advanced ICTs. The inclusion of "sustainability" in the smart city concept has also been confirmed by recent research in the form of reviews of the smart city domains. For example, Neirotti *et al.* (2014) identify environmentally friendly policies as a primary contextual factor that effects how smart cities are developed. In another review of 61 applications from 33 smart cities, Zubizarreta *et al.* (2015) found that environment-related applications occupy 18.03 per cent of the total, rendering the environment dimension an integral part of the smart city. Albino *et al.* (2015) confirm that issues related with the environment, energy and sustainability in cities are included in many definitions of the smart city.

Still, the presence of the environmental dimension is rather abstract in the smart city literature, with the specific subdomains, objectives, measures and performance metrics left largely unaddressed (Komninos *et al.*, 2016). This poses a very specific challenge for the orientation of smart cities toward sustainability goals, given that the "smart city" is more of a strategy than a reality, a strategic vision for the future and as such, smart cities should be approached systematically and holistically (Komninos, 2011; Nam and Pardo, 2011; Schaffers *et al.*, 2012). Smart cities stand for an idea of where the city wants to be in the future and how it imagines itself transformed by taking advantage of the capabilities of digital technology and innovation networks. In most cases, it is not something that can be achieved here and now, but at best a strategic approach toward fulfilling a long-term aspiration. To become a smart city, a set of requirements apply: a comprehensive sequence of strategic choices, a great deal of commitment of resources, monetary investment and the involvement of stakeholders with sometimes overlapping or conflicting roles. All these need coordination and handling in accordance with a clearly defined policy framework.

2.3 Smart and sustainable cities. An emerging paradigm and the contribution of information and communication technologies to sustainable urban development

In recent years, the introduction of the "smart sustainable city" has been proposed as an alternative to the two standalone terms of the "smart city" and the "sustainable city", with the aim of securing the existence of a sustainability dimension within smart city initiatives, tools and applications (Ahvenniemi *et al.*, 2017; Bibri and Krogstie, 2017; Ibrahim *et al.*, 2015; Kobayashi *et al.*, 2017; Kramers *et al.*, 2014). The smart sustainable city, a concept that emerged in the mid-2010s, has been defined as:

> [. . .] an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects (International Telecommunications Union, 2015).

This definition is very close to the one assembled by Höjer and Wangel (2015) through a deductive approach while accounting for the origins of the concept of sustainability in the classic definition of sustainable development of the Brundtland report (Brundtland, 1987). Nevertheless, there are many different definitions, as it is difficult to define a concept that is the intersection of two other concepts that are already contested in themselves.

According to Höjer and Wangel (2015), five different developments drove the emergence of the "smart sustainable cities" concept in recent years:

(1) the realization that environmental problems are global and that sustainable development should be pursued at all levels (global and local);

(2) the increasing trends in urbanization that bring cities to the epicenter of interest in the sustainability discussion;
(3) the rise of the sustainable urban development and sustainable cities movement in an effort to take local action for sustainable development;
(4) the technological leaps in ICTs over recent years, with an enormous impact on society, economy and environment; and
(5) the emergence of the smart cities concept toward the end of the twentieth century, in a setting of so-called "entrepreneurial urbanism".

The essence is that in smart sustainable cities, online tools and platforms contribute significantly to the repression of energy requirements and pollution and hence drive cities to a more environmentally sustainable economy (International Telecommunications Union, 2014). For example, online tools minimize the necessity for physical travel and the existence of physical workplaces. Collective intelligence approaches nurture the conscience of users regarding energy, making them aware of their own resource consumption within the collective consumption pattern. External greenhouse gas reduction and health benefits are achieved through the development of applications for sharing of resources, cleaner environment, waste management, etc. Moreover, intelligent technologies impact citizens' well-being and financial stability (Ahvenniemi *et al.*, 2017). Online platforms and decision support systems also enhance flexibility and responsiveness to unexpected circumstances, as cities can use real-time information to monitor urban functions and detect patterns and anomalies that will eventually allow them to become more flexible, responsive and resilient (Huston *et al.*, 2015; Marsal-Llacuna *et al.*, 2015). In the context of the Global E-Sustainability Initiative (2012), four so called "change levers" are identified toward abating emissions through ICT enabled solutions:

- digitalization and dematerialization;
- data collection and communication;
- system integration; and
- process, activity and functional optimization.

In the following three paragraphs, we describe three different approaches at the intersection of the "smart" and "sustainable" city concept.

First, based on the review by Hilty *et al.* (2011), ICTs can play a defining role in how sustainable urban development will evolve in the future. This is because ICTs possess features that will contribute to a less material-intensive economy, which in turn would allow for increased decoupling of resource consumption and consequently a decreased environmental impact from economic growth. In most cases, the particular focus of smart sustainable cities is set on whether and how smart city tools, applications and platforms contribute to sustainable urban development. It further examines the extent to which sustainable urban development frameworks are capable of incorporating and capitalizing on the new opportunities stemming from the smart city (Bibri and Krogstie, 2017). In this sense, "sustainable" is seen as a normative concept and "smart" as an instrumental one (Höjer and Wangel, 2015). This approach coincides with ours in this paper.

A different approach to ICT, sustainability and urban intelligence is proposed by Bifulco *et al.* (2016), whereby ICTs and sustainability are both considered as enabling forces of city smartness, smart city planning and smart growth (instead of sustainability being an outcome of smart city practices). The authors found that in current policy-making,

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sustainability is strongly associated with smart city *governance, economy* and *people* [following the smart city categories of Giffinger *et al.* (2007)], and less strongly associated with *mobility*, *environment* and *living*. Adversely, ICTs are strongly associated with the *environment* category, among others. This might suggest that there is room for improvement of sustainable development policy and measures in the environmental domain by exploiting ICT applications that are available in this same domain.

In another recent study, which represents the third approach, Ahvenniemi *et al.* (2017) explored the extent to which the concept of the smart city shares common grounds with the one of the sustainable one, by means of comparing assessment frameworks from both categories. The authors found that smart cities tend to prioritize social sustainability targets over environmental and economic ones. Smart city indicators in environmental sustainability-related domains (such as "natural environment", "water and waste management", "transport and energy" and "built environment") clearly occupy a small part of the pie of available smart city indicators as a whole.

Moreover, according to Höjer and Wangel (2015), smart sustainable cities will soon have to address the following challenges:

- methods, practices and strategic assessment of the smart sustainable city need to be defined;
- mitigation measures need to be introduced, as advancements in sustainability or ICTs risk leading to overconsumption of resources because of increased efficiency;
- there is a challenge in scoring the right mix of bottom-up and top-down intervention toward the desired goals;
- an advanced strategic competence of local administrations will be needed, so that they will be able to articulate a vision for the smart sustainable city and specify their needs accurately; and
- governance and coordination of smart sustainable city stakeholders is also required.

An important and extremely ambitious challenge/trend that has emerged within the field of smart cities is that of "zero vision". Zero vision refers to the use of smart city technologies to achieve highly ambitious targets of zero negative impacts in cities and to become fully sustainable, offering their citizens a high quality of life (Komninos, 2016b; Zaman and Lehmann, 2013). Zero-vision strategies can be applied to various domains of the city, including zero traffic accidents, zero CO_2 emissions, zero crime, zero waste, etc. Although such strategies are expected to play an important role in the future of cities, research in this area remains rather limited, mainly focusing in the field of transport. More specifically, the vision of zero harm (harm zero) which started as a business practice was adopted by Sweden, and afterward by many municipalities worldwide (New York, Boston and Seattle), as a strategy for road safety and the elimination of deaths and serious injuries resulting from traffic accidents. The concept is based on the belief that no human loss is an acceptable price for mobility. Recently, the notion has been broadened because of its connection with digital technologies and the scope of smart cities that cover many aspects of urban living. It has now been adopted as a multinational initiative aiming at eliminating deadly risks and all kinds of threats within cities, ranging from advancing the safety, health and well-being of citizens to ensuring the protection of the environment. This means that zero vision refers to strategies and action plans that result in zero CO_2 emissions (), zero fatal traffic accidents, zero waste and zero aggression in the public space of cities (Komninos, 2016a; Zaman, 2014). What is more, they are long-term strategies which require changes not only in infrastructure

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and legislation but also in the culture and way of living within the city. Urban planning, education, public services, digital technologies, are all part of the solution for "zero vision".

3. Research design

3.1 Research aim

Smart city applications address various environmental problems and challenges that cities with growing urbanization are facing today. These include traffic congestion, air pollution and waste disposal (Bhatta, 2010; Broere, 2012; Ferguson and Dickens, 1999). Moreover, software applications are a core component of the multi-layer architecture of the technology stack for smart cities (Komninos *et al.*, 2014), as they act as integrators of heterogeneous ICT hardware, data, user engagement and urban processes (Tsarchopoulos *et al.*, 2017). However, these applications vary significantly both in terms of purpose and in terms of function. Considering digital technologies as an enabling feature of smart cities, the questions we wish to discuss in this paper concern what kind of digital applications cities can currently use to tackle environmental issues, identify the main trends and detect gaps on technical and policy levels. Moreover, we examine whether these applications could attain the "zero vision" objective.

3.2 Research approach

To address these questions, we analyzed 32 applications addressing environmental sustainability issues that can be found in the Intelligent/Smart Cities Open Source (ICOS) community repository (ICOS, 2017). ICOS is a meta-repository for intelligent/smart cities applications and solutions, addressed to city authorities and application developers with the aim of facilitating the uptake and implementation of smart city solutions (Komninos *et al.*, 2016). Each application is categorized by the domain it serves ("Innovation Economy", "Living in the city – Quality of life", "City Infrastructure and utilities", "City Governance" and "Generic") (Table I), the type of software it uses, its technical characteristics and license type. These four domains correspond to the classic structuring elements of cities, the production and consumption subsystems, their network system and the pertinent government system (Castells, 1974). Based on their relevance with the topic of this paper, the applications selected for this research are included in the domains of "City infrastructure and Utilities" and "Living in the city – Quality of life" and they are listed in (Digital applications assessed [authors' elaboration]).

AirCasting http://aircasting.org/ (accessed 22 April 2017):

- AirCasting is an open-source, end-to-end solution for collecting, displaying, and sharing health and environmental data using either a smartphone or a specially designed device called AirBeam.

City function	No.	(%)
Innovation economy	11	8.46
Living in the city – quality of life	25	19.23
City infrastructure and utilities	24	18.46
City governance	39	30.00
Generic	31	23.85
Total	130	100.00

Source: ICOS, 2017

Table I. Software applications in the ICOS repository

Bigbelly SmartWaste & Recycling http://bigbelly.com/places/cities/ (accessed 24 April 2017):

- A smart waste and recycling system designed for public spaces, comprising modular components that enable cities to deploy waste, recycling and even compost stations that meet the needs of each station locations.

Building Energy Benchmarking http://visualization.phillybuildingbenchmarking.com/#/map (accessed 24 April 2017):

- A visualization tool that makes it possible for cities to view energy usage for individual buildings. Through maps, charts and statistics, it is possible to hone in on a region of interest and view energy usage statistics of individual buildings.

DROMS www.auto-grid.com/products/droms (accessed 14 June 2016):

- A demand response optimization and management system, aiming to predict and control millions of connected distributed energy resources across the Internet.

Energy Data Platform http://icos.urenio.org/applications/energy-data-platform/ (accessed 14 June 2016):

- A software that allows utilities and new energy providers to integrate intermittent renewables like wind and solar on a large scale into their operations and introduce new technologies like energy storage or EV charging quickly and economically.

Enovo for Cities www.enevo.com/enevo-cities/ (accessed 24 April 2017):

- A sensor-based solution that aims to increase efficiency and transparency in waste management. Through tracking container fill-levels and optimizing pickup routes, this solution tries to improve cost efficiency, as well as reduce the environmental footprint of the waste.

Everimpact www.everimpact.org/#home (accessed 4 January 2017):

- An application that monitors climate in cities to discover the origins of greenhouse gas emissions in cities. It measures and monetizes cities' CO_2 emission by combining satellites and ground sensors' data.

Hoyrespiro http://hoyrespiro.people-project.eu/ (accessed 15 September 2012):

- A Web application providing information about city air quality extracted from a city's pre-existing environmental monitoring networks. It provides a rapid and effective technological answer to the needs of people with special sensitivity to environmental allergies.

Is there sewage in the Chicago River? http://istheresewageinthechicagoriver.com/ (accessed 14 June 2016):

- An online platform providing real-time information about the dumping of sewage into a river.

LeakView www.visenti.com/?page_id=206 (accessed 24 April 2017):

- An advanced sensing platform for real-time detection of pipe breakages. The system comprises multiple pipe leakage indicators (high-rate pressure sensors, hydrophones and flow meters installed at optimal locations) coupled with data analytics for anomaly detection.

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Mapdwell Solar System www.mapdwell.com/en/solar (accessed 24 April 2017):

- Mapdwell Solar System is an interactive online rooftop solar mapping tool. It allows users to precisely estimate rooftop solar electric potential (PV panels) for almost every building in a given city by a simple click or by inputting an address.

MATSim www.matsim.org/ (accessed 23 May 2012):

- An open source framework to implement large-scale agent-based simulations. Different scenarios can be supported by this model, such as air pollution from traffic, city evacuation in case of emergence, traffic simulation.

Metropia Synergy www.metropia.com/ (accessed 14 June 2016):

- An advanced platform enhancing urban transportation system efficiency by influencing personal travel behavior decisions. Using proprietary algorithms and data analytics, it provides a framework to enhance and monitor the transportation systems' performance.

My building doesn't recycle http://mybuildingdoesntrecycle.com/ (accessed 14 June 2016):

- A Web application that allows multi-unit renters (with five or more units) to crowdsource data informing about recycling activity.

MyCity360 – Smart Parking http://mycity360.co.il/# (accessed 4 February 2017):

- An integrated solution to the parking search problem. The system consists of a smart app that monitors and controls sensors deployed on the curb-side, as well as in garages around town and communicates the information in real-time to the drivers.

Openair www.openair-project.org/ (accessed 23 May 2012):

- A Web-based platform providing a collection of open-source tools for the analysis of air pollution data. It uses the statistical/data analysis software *R* as a platform, which offers a powerful, open-source programming language ideal for insightful data analysis.

OpenTreeMap www.opentreemap.org/ (accessed 18 March 2012):

- A Web and smartphone application, which provides an easy-to-use public inventorying platform enabling individuals, organizations and governments to collaboratively create interactive and dynamic maps of a community's tree population.

OpenTripPlanner www.opentripplanner.org/ (accessed 5 March 2012):

- A multi-modal trip planner, which allows users to schedule transit, travel and map information. It gives detailed step-by-step directions along-side interactive route maps, details of public transport services required and transfer information.

ParkSight www.streetline.com/parking-analytics/ (accessed 14 June 2016):

- A cloud-based, software-as-a-service (SaaS) application that allows cities access both real-time and historical parking data and aims to make optimal and efficient use of parking resources.

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Reroute.it http://icos.urenio.org/applications/reroute-it/ (accessed 25 September 2013):

- A mobile application to calculate the costs and environmental impacts of transportation choices, combining all modes of transit.

Smart Citizen https://smartcitizen.me/ (accessed 14 June 2016):

- An open source platform for crowdsourced environmental monitoring. Connecting data, people and knowledge, its objective is to serve as a node for building open indicators and distributed tools, and thereafter the collective construction of the city for its own inhabitants.

Smart + Connected lighting https://goo.gl/JIdZ5g (accessed 13 July 2016):

- A solution for a powerful light-sensory network (LSN) that gathers a wide variety of data from the environment. These data can support many city services across a common infrastructure: from law enforcement to environmental improvement, transportation oversight, etc.

Smart + Connected parking https://goo.gl/TQx7yx (accessed 13 July 2016):

- The solution gathers and delivers the data by combining Wi-Fi infrastructure with IP cameras, sensors and smartphone apps. It provides visibility into parking analytics, including usage and vacancy periods, which helps cities with long-term planning.

Smart + Connected Traffic https://goo.gl/TIavQV (accessed 13 July 2016):

- A solution addressing two major challenges for cities: road safety and congestion. It helps traffic departments accurately detect more incidents, early on, before they become more serious and enables quicker response by monitoring and analyzing traffic flow data.

TRACE https://esmap.org/TRACE (accessed 23 April 2017):

- A decision-support tool designed to help cities quickly identify under-performing sectors, evaluate improvement and cost-saving potential and prioritize sectors and actions for energy efficiency intervention.

TransBASE http://transbasesf.org/transbase/ (accessed 14 September 2016):

- An online database and analytical tool that facilitates a data-driven approach to understanding and addressing transportation-related health issues. Using an open source relational database management system, it aims to inform public and private efforts to improve transportation system safety and public health.

Treepedia http://senseable.mit.edu/treepedia (accessed 24 April 2017):

- An interactive Web application that measures cities' green spaces. It allows users to view the location and size of their city's trees, submit information to help tag them and advocate for more trees in their area

Urban Engines http://icos.urenio.org/applications/urban-engines/ (accessed 14 June 2016):

- A cloud-based solution providing visibility into transit system performance and commuter. Combining big data and spatial analytics, it attempts to improve urban mobility and help cities make better decisions about transportation.

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WasteOS https://compology.com/ (accessed 26 April 2017):

- A dynamic routing system built for the waste management. It uses software and sensors to lower costs of services by building, delivering and analyzing the most efficient routes for a fleet.

Water Storage http://bit.ly/2oPNQKq (accessed 15 September 2012):

- An interactive dashboard providing access to information for publicly owned water storages across Australia. Through standardizing nationwide data, it permits comparisons related to how the volume has changed over the previous year, month, week and day.

WaterSim http://wsuied.watersimdcdc.org/ (accessed 5 September 2016):

- A simulation model created to estimate water supply and demand. Users can explore how water sustainability is influenced by various scenarios of regional growth, drought, climate change impacts and water management policies.

WaterSmart www.watersmart.com/ (accessed 14 June 2016):

- A cloud-based platform for data-driven water demand management. It uses data analytics to maximize water-use efficiency and improve financial forecasting accuracy through engaging citizens.

To examine each application from the above sample, we defined a series of research components that help us identify their main characteristics and analyze them comparatively. More specifically, the applications are classified according to the *environmental issue* they address, namely:

- high traffic density;
- high amount of waste;
- increasing air pollution;
- increasing energy consumption/sinking resources;
- loss of biodiversity and natural habitat; and
- sinking water resources.

Then, each one of them is associated to one or more *mitigation strategies*, as they are found in the literature (Riffat *et al.*, 2016) and adjusted to the focus of the current research on the digital dimension. Among these strategies, we identify:

- having efficient transportation systems;
- incorporating compact city design;
- ensuring waste management and recycling;
- increase green space;
- decreasing CO_2 capture;
- reducing atmospheric pollution;
- using renewable sources;
- achieving low energy buildings;
- increasing efficiency of devices and processes,

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- developing animal and/or plant protection areas; and
- maximizing water use efficiency.

Advancing to the specific characteristics of each application, we focus our attention on the *innovation mechanism* that is activated, the role of ICTs and their outcome. More specifically, we examine where the actual innovation is concentrated:

- whether technology is the main enabler and without it the application could not have been realized;
- whether innovation lies on the process level, disrupting the involved roles, relationships and transactions; or
- whether citizen engagement and participation activate the innovative element of the application.

The description of the role of *ICTs* is based on what kind of functions it enables, such as:

- information and knowledge sharing (mainly real-time data allowing for a view of the current situation);
- forecasts (historical and/or real-time data allowing to identify patterns and trends); or
- integration (sourcing and combining of data from various smart infrastructure management systems) (International Telecommunications Union, 2014).

Finally, the *outcome* of the application is assessed, regarding whether it is focused on:

- sharing information and resources;
- identifying problems and underlying issues;
- actually solving those problems; and/or
- support or influence decision-making and policy-making (Davies and Simon, 2014; Millard *et al.*, 2013).

The findings from the above analysis are presented in the next section and they are summarized in the Annex (Tables III-VIII).

4. Findings

The findings of this research are based on the analysis of the aforementioned 32 applications related to six main challenges of environmental sustainability in urban environments, as presented in the research methodology. The sample almost equally comprises open source and proprietary applications: 15 and 17 correspondingly (Figure 1). Among them, a significant part is related to sustainable mobility themes, ranging from multi-modal transit planning and simulation tools to applications promoting an efficient use of parking resources. Regarding the remaining environmental challenges, between three and six applications were found per category. More specifically, five applications related to air pollution were identified, all of which are open source tools promoting the collective monitoring of air quality. Regarding biodiversity and natural habitat, two applications are focused on inventorying and measuring tree population in cities and one in river protection from sewage dumping. Applications related to waste management are focused mainly on tracking container fill levels and thus optimizing pickup routes and less on recycling activities. As far as energy consumption is concerned, the applications that have been

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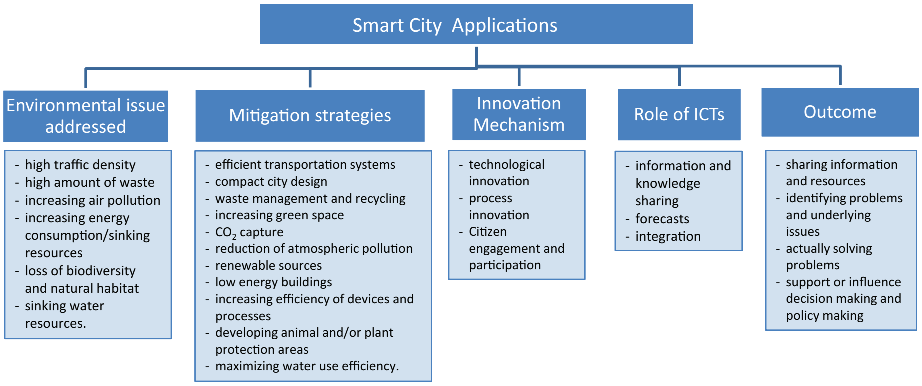

Figure 1.
Research components of smart city applications

identified, mainly proprietary, include visualization and other decision-support tools that integrate data from different sources into a single management platform. Finally, water usage and demand management, as well as real-time leak detection, are among the purposes of the applications related to water resources.

A more detailed overview of our research findings is presented below, divided into two parts. The first one is focused on each environmental challenge individually, highlighting the most common trends, as well as the gaps that are identified for each component. The second part examines the sustainability challenges comparatively with respect to their components as defined in the research design section.

4.1 Sustainability challenges addressed (individually)

Regarding the high traffic density challenge, the findings suggest that mitigation strategies focus mostly on rolling out more resource efficient transport systems. Secondarily, this challenge is mitigated by means of designing urban areas on the basis of compact city principles, and increasing the efficiency (capacity) of the devices and processes used. Innovation mechanisms are all driven by technology, with process and civic innovation being absent for the most part. ICT functions are mostly focused on forecasting traffic congestion to provide route optimization advice. Less emphasis is given to the functions of information and knowledge sharing and technology integration. The foremost outcomes include making optimal decisions, identifying problems – such as mapping of congested areas – and to a much lesser extent solving problems and simply sharing information and resources.

As per the high amount of waste challenge, the findings reveal that mitigation strategies are highly concentrated on increasing the efficiency and capacity of the equipment used, followed by waste recycling programs and initiatives combined with the use of renewable sources of energy in some cases. Innovation mechanisms in the waste management applications sector are also highly driven by technology and secondarily by citizen engagement. ICT functions are focused on information and knowledge sharing and forecasting. Specific outcomes are concentrated on solving problems and making decisions, followed to a lesser extent by outcomes in the areas of sharing information and resources and identifying problems.

Concerning the challenge of increasing air pollution, all mitigation strategies are focused on capturing CO_2 emissions. Innovation mechanisms are dispersed across the three different areas of focus, namely, technology, processes and citizen engagement. The most commonly encountered ICT functions enable information and knowledge sharing, forecasting and

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technology and information integration. The outcomes in this category are highly concentrated on problem identification, followed by sharing information and resources.

In the increasing energy consumption/sinking resources category of challenges, two major mitigation strategies prevail: the renovation or construction of low energy buildings and the increase in the energy efficiency of used devices/processes. Again, technology plays a primary role as an innovation mechanism, followed by process innovation. In terms of ICT functions, forecasting of energy consumption is the foremost function addressed, followed by technology integration across various platforms and devices. Finally, in terms of outcomes, the most common one is the one of making better and more informed decisions, followed by the ability to identify and solve problems.

Advancing to the next challenge, loss of biodiversity/natural habitat, the majority of mitigation strategies are focused on increasing the surface of green and open spaces in the city and secondarily on creating animal and plant protection areas. Innovation mechanisms in the category are solely focused on process innovation. The majority of ICT functions are found in forecasting, followed by sharing of information and knowledge. Finally, the outcomes are equally set on sharing information and resources and identifying underlying problems.

In the last challenge category, which is sinking water resources, the total of mitigation strategies is focused on maximizing the efficiency of water usage. Innovation mechanisms are concentrated around technology, followed by process innovations. The largest fraction of ICT functions are set on forecasting and secondarily ICT integration. The outcomes are important in two categories, namely, problem identification and decision-making, followed to a lesser extent by information and resources sharing.

4.2 Sustainability challenges addressed (comparatively)

In this section, we compare the sustainability challenges on the basis of our research components. As per the innovation mechanisms that are used in tackling urban sustainability challenges (Figure 2), the findings are the following:

- Technology innovation is especially pertinent to the challenges of traffic congestion, energy management, water and waste management. Areas that lag in terms of technology innovation include air pollution and lack of biodiversity monitoring and mitigation.

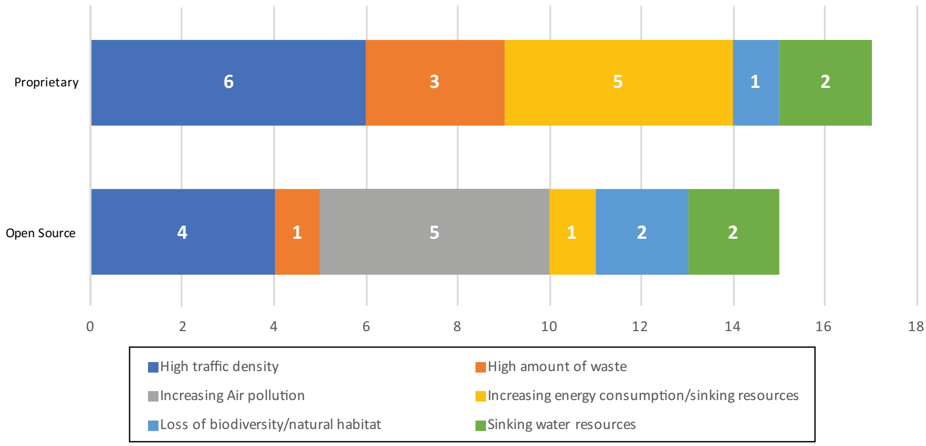

Figure 2.
Applications distribution according to environmental issue and property

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- Procedural innovations are especially common in the areas of biodiversity loss. Some are existent for mitigating air pollution and sinking water resources, too. Gaps exist in the challenges of waste and traffic congestion management.
- Finally, innovation by means of new forms of citizen engagement is altogether very low, with only a few applications existing in the areas of waste and air pollution management.

Regarding the role of ICTs in tackling sustainability challenges (Figure 3), we find that:

- Real time information and knowledge sharing applications are most common in the areas of waste management and air pollution. For the challenges of traffic congestion, sinking water resources, lack of biodiversity and energy consumption there few or no applications.
- Forecasting applications exist mostly for mitigating energy consumption, traffic congestion, water consumption and biodiversity loss.
- A few integrated ICT systems that would be able to transmit information across various devices are available for the challenges of traffic congestion, sinking water resources and lack of biodiversity. A gap exists in all other sustainability challenge areas.

Advancing to the outcome of the studied ICT applications (Figure 4), the conducted analysis suggests that:

- Most applications enable problem identification and reporting, usually on maps and by using different devices;
- A large number of applications allow urban stakeholders to make decisions about how to act upon a challenge, especially in the areas of mobility, energy, water and waste management;
- A few applications support a function of sharing of information and resources, namely, in the areas of air pollution and lack of biodiversity; and
- Very few applications result in solving problems, with the only exception the challenge of waste management (Figure 5).

Altogether, there appears a very fragmented landscape of ICT applications in the different topics of the research, namely, ICT functions, innovation mechanisms and outcomes. Lack of

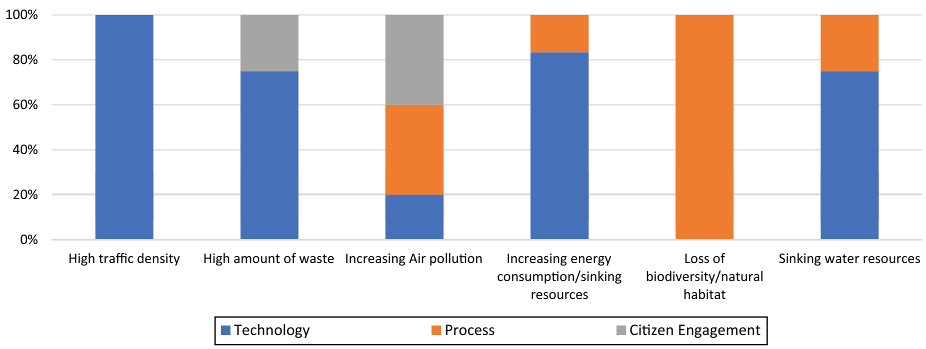

Figure 3. Distribution of innovation mechanisms per challenge addressed

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biodiversity/natural habitat preservation is the most underrepresented sustainability challenge in all areas, followed by sinking water resources. A possible explanation for this is that natural habitat and water are more difficult to monitor and control, as they carry highly supra-local characteristics that create phenomena especially challenging to monitor, let alone improve. The areas of traffic management, waste management, air pollution management and energy consumption management (in descending order) appear to be more holistically addressed through existing smart city applications, although gaps still do exist in those areas. At the same time, these areas of ICT applications are highly relevant to the implementation process of the "zero vision" strategy. More specifically, applications related to traffic, air and waste management contribute to the vision toward zero carbon dioxide emissions (CO_2), zero fatal traffic accidents and zero waste in cities.

5. Conclusions

In this paper, we examined the availability and characteristics of smart city applications in the domain of sustainable urban development, addressing the specific sustainability challenges of green motorized mobility, waste, air pollution, energy consumption, urban biodiversity and water management. More particularly, we identified and analyzed 32 open source and proprietary applications addressing the above challenge areas, classifying the findings in accordance with mitigation strategies, ICT functions, innovation mechanisms and outcomes. In doing so, we identified underlying trends, as well as research and

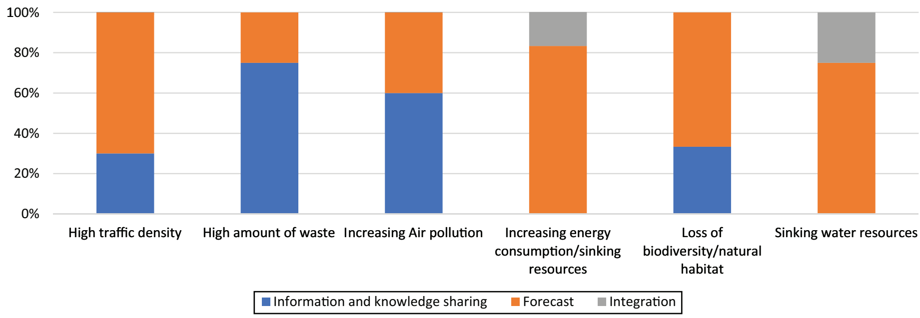

Figure 4.
Distribution of ICT functions per challenge addressed

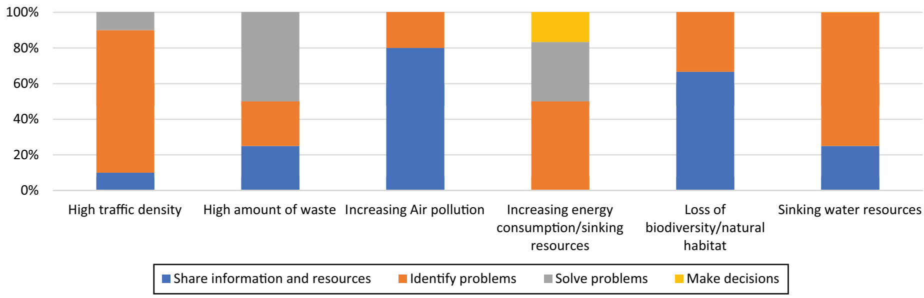

Figure 5.
Distribution of outcomes per challenge addressed

development gaps in the smart city applications domain. The findings are of special interest to policymakers, application developers and user communities.

The overarching conclusion from this work is that the smart and sustainable city landscape is extremely fragmented both on the policy and the technical levels. There is a host of unexplored opportunities toward smart sustainable development, as well as toward the "zero vision", many of which are still unknown. Capitalizing on these opportunities, however, would call for different and innovative ways of thinking and acting.

More particularly, on the technical level, we identified the following largely unaddressed niches:

- in the green mobility domain, integrated, crowdsourced digital applications that allow a sharing of information on traffic congestion and events affecting urban mobility;
- in the waste management domain, integrated applications that allow for process innovations in sharing information and identifying problems;
- in the air pollution domain, integrated technology driven applications that allow urban stakeholders to make decisions and solve problems;
- in the energy consumption domain, crowdsourced applications that allow consumers to share information and resources;
- in the urban biodiversity loss domain, technology driven and crowdsourced applications that allow stakeholders to solve problems and make decisions; and
- in the water management domain, crowdsourced applications and process innovations that allow stakeholders to make decisions and solve problems collectively.

To encourage the closing of the above gap, specific actions are needed on the policy level. We could distinguish those actions in horizontal and vertical (thematic) measures. Horizontally, policymakers need to make a concerted, long-term effort to become proactive, knowledge-driven and more responsive to their constituents' needs, by building their internal capacity to quickly process background information and drawing on new and alternative forms of knowledge generated by their stakeholder communities. In this journey, "open government" concepts can guide policy-making, in the sense of advocating urban stakeholders' rights to access government information, propose new ideas and become agents of change. One could not overlook that opening up municipal and government data and any data concerning the city in general is a precondition for this. Both historical and real-time data are needed. Data also need to be accurate, meaningful and in actionable formats. Effective and reliable urban development policies need to consider any available data (including their structure and topology) and evidence to access accurate and meaningful information that may lead to better results, more targeted actions and eventually boost the endogenous urban and social development dynamics that exist within every human community. In this given case, the incorporation of the systematic use of big data and real-time data in the policy development and monitoring process is a key success factor toward better policy design and implementation, with significant positive impacts on contemporary societies on multiple levels.

In a parallel line of thinking, specific policies are required to support and encourage entrepreneurship and startup creation in the domains of digital services and development of data-driven applications, especially in the areas where technical gaps exist. The sustainability landscape is so vast that no local government can address smart city service gaps alone, as governments are typically constrained by bureaucracy and limited human and financial resources. Sustainability is also highly locale specific, in the sense that cities are called to address different challenges depending on their size, climate, structure and topography. Hence, (local) policymakers should focus on encouraging the development of

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vibrant local entrepreneurship ecosystems that enable new forms of place-based collective intelligence and capitalize on local knowledge spillovers. To this end, actions can be taken toward nurturing the creation of communities and networks of startups and entrepreneurs, creating programs and providing incentives for entrepreneurs to concentrate their activity toward the identified technical and local sustainability deficits.

Furthermore, our study revealed that there is a very important research gap in how policy for sustainability can be bridged with smart city technical level requirements to address specific needs and market niches in the urban sustainability domain. To address this gap, governments could encourage the advancement of two different streams of research in academia and industry. The first one is about the specific details of how and which smart city applications can work together toward sustainable urban development. Possible research questions in this direction would include: What is the best smart city application for a specific sustainability challenge and why? What are the factors that determine the features and requirements of each smart city application and the selection of a specific smart city application over another? How can an application be assessed for its contribution to environmental, social and economic sustainability? Can there be synergies among the employed smart city applications? The second stream of research explores the share and characteristics of smart city application market niches in the urban sustainability domain. Possible research questions in this direction would include: Which are the market segments in the smart city applications for urban sustainability domain? How dynamic and promising are they? Are there new emerging market segments that have not yet been identified? In essence, both of the aforementioned cross-thematic domains offer promising and fertile grounds for research that, if encouraged by government, can open the way for new, improved lines of thinking and act toward urban sustainability.

Moreover, policy measures need to be taken on a vertical level. By looking at the specific challenges of (environmental) urban sustainability – namely in mobility, waste, air pollution, energy consumption, urban biodiversity and water management – policymakers can develop highly accurate, targeted and ultimately more effective thematic policies and strategies, as in the case of the "zero vision" strategy. This paper provides resources about the available options and action routes in the domains concerned. Moreover, the aforementioned technical market niches can be used to encourage research and development in these largely unaddressed areas.

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