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TCitySmartF: A Comprehensive Systematic Framework for Transforming Cities Into Smart Cities

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ABSTRACT A shared agreed-upon definition of "smart city" (SC) is not available and there is no "best formula" to follow in transforming each and every city into SC. In a broader inclusive definition, it can be described as an opportunistic concept that enhances harmony between the lives and the environment around those lives perpetually in a city by harnessing the smart technology enabling a comfortable and convenient living ecosystem paving the way towards smarter countries and the smarter planet. SCs are being implemented to combine governors, organisations, institutions, citizens, environment, and emerging technologies in a highly synergistic synchronised ecosystem in order to increase the quality of life (QoL) and enable a more sustainable future for urban life with increasing natural resource constraints. In this study, we analyse how to develop citizen- and resource-centric smarter cities based on the recent SC development initiatives with the successful use cases, future SC development plans, and many other particular SC development solutions. The main features of SC are presented in a framework fuelled by recent technological advancement, particular city requirements and dynamics. This framework — TCitySmartF 1) aims to aspire a platform that seamlessly forges engineering and technology solutions with social dynamics in a new philosophical city automation concept — socio-technical transitions, 2) incorporates many smart evolving components, best practices, and contemporary solutions into a coherent synergistic SC topology, 3) unfolds current and future opportunities in order to adopt smarter, safer and more sustainable urban environments, and 4) demonstrates a variety of insights and orchestrational directions for local governors and private sector about how to transform cities into smarter cities from the technological, social, economic and environmental point of view, particularly by both putting residents and urban dynamics at the forefront of the development with participatory planning and interaction for the robust community- and citizen-tailored services. The framework developed in this paper is aimed to be incorporated into the real-world SC development projects in Lancashire, UK.

INDEX TERMS Smart city, crowdsourcing, Internet of Everything (IoE), cloud, edge/fog/MEC, smart planet, IoT.

I. INTRODUCTION

Today, and every day, worldwide, one million more people are born-into or move-into a city, and it is envisioned that this will continue for the next 30 years at least [1]. The global population is expected to double by 2050 [2] and more than 68% of the population will be living in an urban environment by 2050, reflecting a speed of urbanisation even faster than previously predicted, most visibly in developing countries [3] with a population of 5 billion [4]. Cities currently face an increasing demand for providing enhanced public services that can have an impact on people's everyday lives [5]. Even though cities cover just 3% of the earth's surface, they drive our economies, they consume 75% of the world's energy and city-based consumption drives 80% of additive greenhouse gases [1]. More explicitly, cities with heavy populations escalate burden on energy, water, buildings, environment, public places, transportation, climate and many other things [6]. The pressure is growing on city governments to leverage every opportunity to improve the quality of life (QoL) for

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inhabitants [7] due to the ever-growing demands of citizens, economic concerns, and imminent environmental risks. In this manner, to alleviate the problems of rapid urbanisation and to improve the liveability of citizens, there are many concerns to be taken into account in urban development and in efficient urban management. Recent advances in cyber-physical domains, cloud, cloudlet, and edge/fog platforms along with the evolving Big Data (BD) analytics, Internet of Everything (IoE), Automation of Everything (AoE) [8], Advanced Insight Analytics (AIA) [8], ubiquitous sensing, location-independent real-time monitoring and control, heterogeneous network infrastructure, and cutting-edge wireless communication technologies (e.g., 5G and beyond) within the Industry 4.0 are providing many opportunities and urging city governors to pursue the ways that enable efficient and intelligent management of cities with effective public services.

The concepts of IoE and AoE bring the people, organisations, lives, processes, data, and things into a concrete coherent structure — cyber-physical systems (CPSs) to develop a synergistic smarter connected globe. In recent years, ''everyday things'' around us have been getting intelligent using CPSs supported by advancing AI techniques enabling self-decision-making with less or no human intervention. The widespread term ''smart'' is being used to indicate the skilfulness of a number of integrated ''things'' to achieve particular missions such as smart home (sHome), smart building (sBuilding), smart industry (sIndustry), smart transport (sTransport), smart shopping (sShopping). In the same context, smart city (SC) is defined as a city connecting physical infrastructures, Information Communication Technology (ICT) infrastructures, social infrastructures, and business infrastructures to leverage the collective intelligence of the city [9] within the concepts of IoE and AoE.

''The physical world is messy and the battle for the planet will be lost or won in our cities'' Steve Lewis, the founder of Living PlanIT, said in his CleanEquity keynote address [10]. In this perspective, various central governments are supporting SC development initiatives. The UK should be seen as a world leader, not just with its smartest cities but also with the companies that develop smart technology according to SCs Forum (SCF) [11]. In 2015, the White House launched the SC initiative which aims to facilitate technological collaboration between cities, federal agencies, universities and the private sector [12]. China has invested heavily in making its cities smart with more than 200 cities [13]. The EU is supporting SC initiatives with big budgets. There are already a number of successful SC examples all around the world, particularly in the USA, EU, and Asia. The global market for SC is expected to be worth between $400-$1200 billion in the following years [4], [11]. Singapore tops the list of cities that will spend the most money on SC projects, together with New York City, Tokyo, and London; each of them more than US$1 billion [14]. Many SC development projects are underway all around the world such as Kansas City [12], Fujisawa [12], Songdo [12], Malmo [12], Hamburg [15], Taiwan [16]. Various SC development projects such as New Songdo in South Korea and Masdar in the UEA tried and failed to deliver a new, smarter and more sustainable way of living [11]. That's because too much emphasis was put on the technology, while not enough attention was paid to the social dynamics [11]. Analysis of the eight SC systems showed that economical indicators were mainly focused and particular environmental indicators and particular city dynamics were not taken into account sufficiently [17]. The sustainability of a city improves as the smartness of a city increases [18]. The current large gap between SC and sustainable city frameworks suggest that there is a need for developing SC frameworks further [17]. It is prime important to learn from not only the best practices but also past mistakes while embarking SC projects. In this perspective, a framework is proposed in this paper to show the directions in developing sustainable smarter cities in a concept of forging best practices with new contemporary solutions by taking unsuccessful SC development attempts into account.

The challenges of urbanisation, if unmet urgently, would entail grave economic and environmental impacts. In this paper, we present the fundamental design concepts of SC based on the analysis of the recent SC practices, evolving technological improvements and new practical solutions to mitigate the imminent burdens of urbanisation on the planet. To clarify the novelty of this paper, the contributions are outlined as follows.

1) Existing SC development projects around the globe along with future SC development plans and multiple SC solutions are analysed in depth, particularly, how cities are putting IoE and AoE into practice successfully with evolving cutting-edge technologies to i) reveal the best practices, ii) unveil novel resource- and citizen-centric, and user-driven opportunities, and finally iii) address the challenges faced in SC development.
2) An idealistic framework with a philosophical aspect—TCitySmartF is proposed with implementation details to facilitate the development of contemporary community- and citizen-tailored platforms with scalable and flexible resource allocation mechanisms for future sustainable SCs. The city productivity and wealth, and QoL within this framework can be increased substantially benefiting every citizen and enabling innovation and economic development.
3) TCitySmartF with a holistic framework draws the border of SC and outlines its components and desired integration requirements not only within itself but also with the national and global smart domains. More explicitly, it demonstrates a dynamic city automation roadmap with appropriate directions driven by particular urban denominators and social dynamics beyond the technological perspective for developing ideal future SCs.

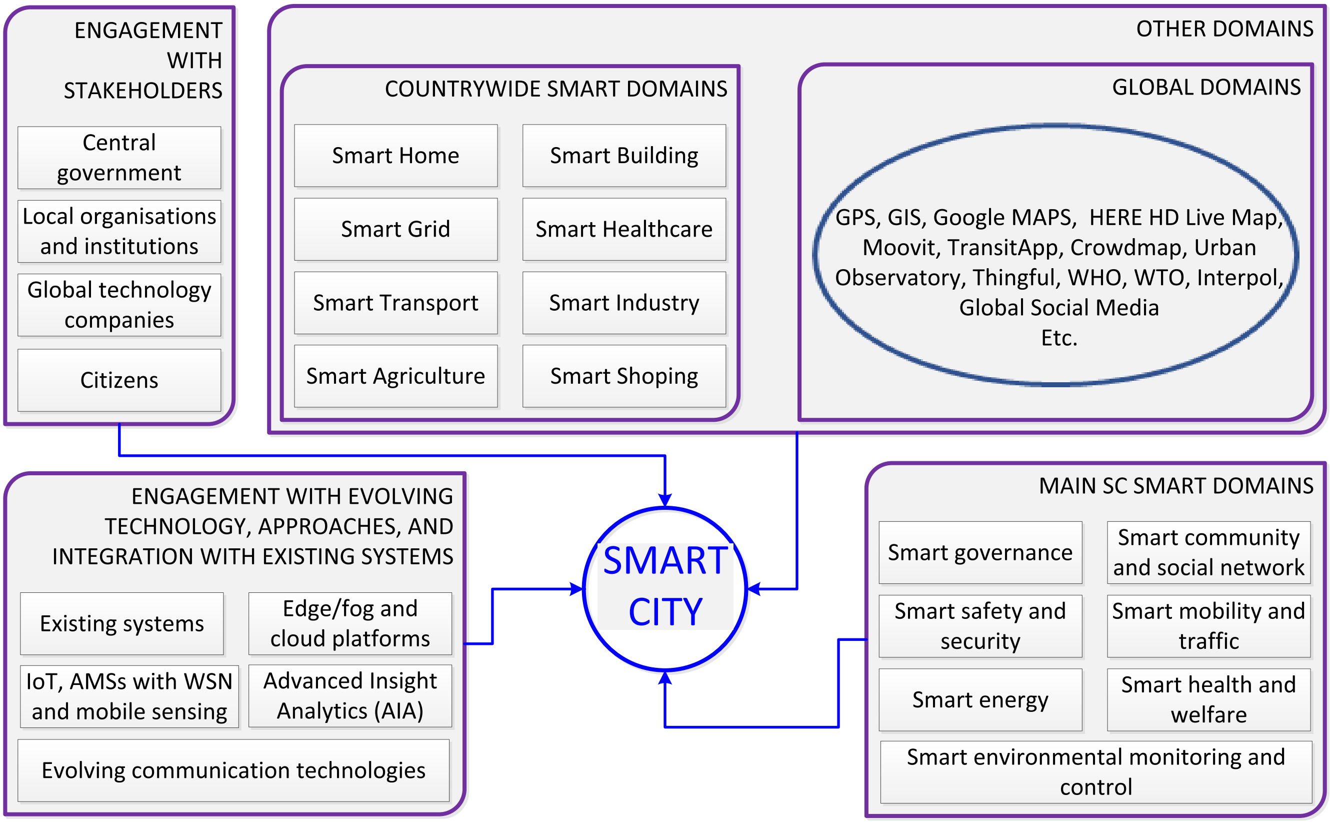

FIGURE 1. **TCitySmartF: Essential elements of Smart City ecosystem involving the national and global smart domains.**

The remainder of this paper is organised as follows. The essential features of SC involving a design architecture with the backbone of SC communication — integrated heterogeneous network, Wireless Sensor Networks (WSN) and highly distributed diverse Internet of Things (IoT) devices along with Advanced Mechatronics Systems (AMSs) are explored in Section II. SCs are not stand-alone systems and synergistic integration with various other national and global domains is addressed in Section III. Security and privacy issues are analysed in Section IV. Section V introduces the essential challenges in SC development. The lessons learned are unfolded in Section VI. The discussion along with open issues is provided in Section VII. Finally, Section VIII draws conclusions and unveils directions for potential future ideas.

II. FEATURES OF SMART CITY (SC)

No two urban environments are the same, as they come with various demographic, social, cultural, and geographical contexts, resulting in significant diversity in SC challenges [19]. In this context, there is no strict "best formula" or "best SC initiative example" to follow in building and enhancing SCs to meet the diverse requirements based on unique characteristics of each city. The recent SC development initiatives with the successful use cases, future SC development plans, and many other particular SC development solutions have been analysed and the ideal features are combined together to establish a SC development framework, so-called TCitySmartF. Main objectives of establishing SCs can be summarised as i) enabling the integration of the distributed services and resources in a combined synergistic fashion, ii) improving existing public services and providing new effective citizen-centric, user-driven, and demand-oriented services, iii) monitoring a city with easy-to-use visualisation tools, iv) enabling near-real-time services for end-users and/or further smart actuation, v) increasing the sustainability with optimised services, and vi) driving economic development, innovation, and global city investment competitiveness.

The essential elements of TCitySmartF is displayed in Fig. 1. TCitySmartF has four dimensions: Engagement with stakeholders, SC infrastructure, SC domains and their integration, and SC integration with countrywide and global domains. The importance of engagement with stakeholders while developing SCs — the first dimension is explained in Section II-A. The technological infrastructure on which SC rises — the second dimension is explored in II-B. The main smart elements of SC — the third dimension is analysed in Section II-C. Finally, the other domains into which SC is incorporated in order to create a synergistic implementation enabling a gate to the development of a group of SCs and consequently smart states and smart countries — the fourth dimension is explicated in Section II-D.

TABLE 1. Successful public sector, local businesses and community engagement initiatives in SC development projects.

Platform examples	Targeted objectives of platforms	City
Engaging the City	to help citizens engage in and understands what the future of Glasgow holds with the SC project — Glasgow Future City using the engagement hubs, interactive content and future explorers programs in order to gain further insights about how the future plans are meeting the needs of the residents [1]	Glasgow
People Make Glasgow	to allow smart people to do smart things by opening up hundreds of non-sensitive and non-personal data sources and by involving and empowering communities, bringing people together to explore their vision for the city and inspiring future generations to make a difference[2]	Glasgow
Memorandum of Understanding	to define a SC framework by bringing representatives of the public sector, research and education institutions as well as local and international companies together [15]	Hamburg
The Urbanflow project	to understand the needs and priorities of individual stakeholders by uniting a number of different departments and stakeholders with a round of interviews [3]	Helsinki
Open Dashboard	to put people at the heart of the city allowing them to tailor their personalised snapshot of Glasgow (e.g., for locals, tourists, cyclists, shoppers), to navigate the city during a busy day to tracking the best times to stargaze at night, to keep track of a city where there's always something happening[4]	Glasgow
City technology platform	to collect data from over 200 streams to understand how the city works [11]	Glasgow
Energy efficiency platform	to enable management systems in different buildings to talk to the power network by working with local businesses, schools, academia and power providers on a pilot project [11]	Glasgow
Citizen science mapping	to gain visitors an insider's perspective by encouraging them to share local knowledge and upload information to an online map [11]	Glasgow
Smart data hub	to allow innovative approaches and development of applications that address city challenges [11] focusing on business, education, and community engagement activities [20]	Milton Keynes
Open data hub	to allow community and researchers to reach over 500 different datasets for generation further insights[5]	London
Open data hub	to let residents find city data, find facts about their neighbourhood, create maps and graphs about the city, and freely download the data for their own analysis[6]	Chicago
Open data hub	to allow community and researchers to reach over 627 different datasets for generating further insights[7]	Helsinki
Open Data of Public Transportation (ODPT)	to build a public transportation open data center offering information on railways, buses, airlines, and all other means of transportation involving 56 corporations [21]	Tokyo
Intelligence Hub	to help make strategic decisions and focus on what communities need so that it can provide the services that will make a difference based on the evidence gathered every day [11]	Sunderland
Smartphone-based local currency app	to enable residents to upload funds to their phones and use them to pay retailers within a public-private partnership for highway infrastructure [11]	Birmingham
Looking Local Digital TV	to give city residents access to information and services through their TV covering jobs, bus and train travel information, as well as a GP booking facility and the ability to view and bid for council properties [11]	Birmingham
Make it Local programme	to reveal what digital services are required to develop both to meet the public's needs and enable the city to work smarter [11]	Birmingham
Smart traffic and mobility	to make all types of transport including delivery smarter in collaboration with the University of Bristol on a research project into the ICT requirements for a demand-responsive public transport system [11]	Bristol
Six step methodology	to enable focusing on supporting people to work together to pull-in the knowledge, technology, and resources needed to tackle a problem, which puts urban digital playfulness at the heart of citizen engagement, making it fun, and which is now being used by Florence, San Sebastian as well [1]	Bristol
Air Quality Dashboard	to help residents access real-time and historic streetwise air quality data [8]	Bristol
SC project openness, Smart street lighting	to allow citizens, building owners, and companies to access camera information and control lighting levels in their vicinity [15]	Amsterdam
Public Wi-Fi	to provide the citizens with online anytime-anywhere connection to the internet, social media and SC applications, which support crowdsourcing application for future smarter city applications [15]	Amsterdam
Real-time dashboards	to collect and display this data in easily readable formats enabling sharing publicly to allow private individuals and organisations to develop further applications in order to make the city smarter [15]	Amsterdam
Energy insight apps	to give people insight into their energy bills on a real-time basis, providing 9 to 14% saving [15]	Amsterdam
Connected Citizens app	to route drivers around congestion by processing crowdsourced data from smartphones (Waze) [22]	Louisville
Citizen dashboard: Greater community knowledge	to make the city smarter by integrating planning, management, and operations both to minimise its carbon footprint and to encourage economic growth based on 11 core principles (e.g., smart use of energy, water, and other resources; green buildings; reasonable mobility) by putting citizens at the centre of a smarter city transformation [23]	Dubuque
Smart Society	to develop and enhance SC with the engagement of citizens using the concept "We are becoming a society for the people, by the people, in which citizens actively identify issues in their city, and every citizen is able and allowed to indicate these issues". In this platform, citizens subsequently collaborate with others to create smart solutions. Solving problems raises QoL [1]	Eindhoven
Monaco 3.0	to encourage residents to engage with a smartphone app that has a crowdsourcing function enabling residents actively to participate in and improve city life by providing the feedback on a fingertip, combined with images and general feedback [24]	Monaco
Satisfaction surveys	to assess citizen satisfaction with services by carrying out annual satisfaction surveys to improve SC [25]	Calgary
MiraMap We-Government tool	to facilitate communication and management between citizens and administration in reporting of issues and claims but also in submitting proposals [26]	Torino
Real-Time-Rome	to aggregate data from cell phones, buses, and taxis to better understand urban dynamics, and help individuals to make more informed decisions [27]	Rome
Complete-Streets	to identify where to place new bike racks using online mapping [9]	Chicago

A. ENGAGEMENT WITH STAKEHOLDERS

Various failed SC initiatives such as New Songdo in South Korea and Masdar in the UEA as mentioned earlier showed [11] that, investing technology immensely can not deliver a desired SC system itself and SC development should incorporate particular social dynamics into the system to be successful. The realisation of urban sustainability around the world relies on extensive collaboration among stakeholders to create, validate, demonstrate technological and social innovations in SC infrastructures and promote comprehensive understanding of scientific, social, and human behaviour aspects of urban development [28]. In this perspective, the vital driver in SC initiatives is the engagement with all the stakeholders to be able to both specify the particular SC requirements and specifications and meet the needs of the residents better based on the particular city dynamics. SC evolves with ongoing brainstorm sessions by unravelling problems, opportunities, and requirements and by coming up with effective solutions and innovative ideas within a concept of collective identity. Rules and regulations for all the stakeholders to comply with should be specified clearly in this collective identity. After analysing current SC initiatives and future plans in many cities, we come to a conclusion that incorporating human dimensions and social dynamics into SC development is made the number one priority. Successful real-world engagement attempts with stakeholders during SC development and enhancement are presented in Table 1. Engagement requirements with the main actors in TCitySmartF in order to develop community- and citizen-tailored platforms involving social dynamics are explained in the following subsections.

1) ENGAGEMENT WITH CENTRAL GOVERNMENT

SC is not a stand-alone system and requires to be integrated with other smart country domains such as smart healthcare (sHealthcare), smart transportation (sTransportation), smart grid (sGrid), smart education (sEducation), smart agriculture (sAgriculture) (Fig 3) not only to develop better synergistic implementations but also not to make the similar things redundant, which is explored in Section II-D. Additionally, coordination with the central government is necessary while developing SC to ensure that the SC applications comply with smart country policies and standards. Therefore, objectives, policies, specifications, and requirements in SC development should be shaped in accordance with the policies and objectives of the central government. Funding support of the central government can be provided as well along with the proper directions.

[1] http://futurecity.glasgow.gov.uk/engaging-the-city/
[2] http://futurecity.glasgow.gov.uk/
[3] http://helsinki.urbanflow.io/
[4] http://futurecity.glasgow.gov.uk/dashboards/
[5] https://data.london.gov.uk/
[6] https://data.cityofchicago.org/
[7] https://hri.fi/en_gb/
[8] https://opendata.bristol.gov.uk/pages/air-quality-dashboard-new/
[9] (http://bikeparking.chicagocompletestreets.org/page/about)

2) ENGAGEMENT WITH LOCAL ORGANISATIONS AND INSTITUTIONS

Residents are the main stakeholders in the city. Universities, other schools, industry, local businesses, non-governmental organisations (NGOs), and all other institutions and organisations are the other very important stakeholders of a city to be taken into consideration. They have demands to be met to perform their tasks effectively and efficiently and they can be the voice of many residents who may not have the chance to point out their needs and thoughts. SC development is not only transforming the cities but also all other elements including those stakeholders are transformed within an orchestrated smart environment. Most importantly, those stakeholders with their immense and immersive background would be a great help in identifying proper requirements and specifications. Their ideas and directions involving their workforce with massive experience would be prime important and must be incorporated into each and every phase of SC development.

3) CITIZEN ENGAGEMENT

Smart environment often remove the occupants from the control loop and can lead to people feeling disengaged from their environment where smarter things are often controlled centrally and do not allow any user input [29]. The main challenge in those autonomous systems is how best to incorporate volatile human behaviours, patterns, and requirements into the heart of autonomous systems. There is only one way of doing this, that is, keeping citizens engaged with their surroundings actively as essentially sensors and/or actuators to some extent enabling evolving systems over the increased control of citizens in their environment. The term, soft actuation with Human-in-the-Loop in conjunction with citizen actuation has been proposed to indicate the actuation triggered by citizens directly or indirectly [30].

While citizens tend to be the implied beneficiaries of SC projects, they are rarely consulted about what they want, and their ability to contribute to making a city work better is often ignored; Citizens must, however, be at the centre of the decision-making process in any SC project if they are to benefit from the intended outcomes [25]. Citizens should not be treated as just some kind of manageable elements and active citizen engagement in SC development and enhancement is the major success criterion. To make cities truly smart for the future we need to make sure that the technology is used to deliver things that people want and need, and that add real value to how life is lived in these cities [5] by engaging with citizens and focusing on the social aspect of urban life within people-friendly environments.

The integration of wireless sensing techniques and mobile devices, such as smartphones is enabling next-generation lightweight people tracking applications for SCs [31]. The world's internet population is growing significantly year by year; as of January 2019, the internet reaches 56.1% of the world's population representing 4.39 billion people - a 9% increase from January 2018 [32]. 6.1 billion people have access to a smartphone and more than half the world's web traffic comes from smartphones in 2019 [33]. It is now a well-established notion that organisations can achieve large-scale, coordinated endeavours by requesting contributions from smartphone users in a context that uses these devices' capabilities. Using citizens' local knowledge, experience, and collaboration could help local officials to obtain an overview of the status of city infrastructure and utilities through crowdsourcing [7] for mapping problems, effective urban management and further planning. Crowdsourcing is revolutionising SCs, particularly real-time smartness of SCs by interacting with entities, citizens or objects. It is an effective technique that incorporates human intelligence and smart machines to collect disparate sensing data in pervasive environments [34] to support sophisticated applications. Proposing that a city's citizens contribute through crowdsourcing activities is a way to benefit from their knowledge of the field [7]. Citizens equipped with smartphones, and smartwatches can be incorporated into the decision-making processes as millions of very intelligent human sensors supported by many other sensors in their smartphones such as camera, GPS, temperature, and accelerometer. In other words, SCs should have the tools to enable users to always interact with the events taking place in their environments. Citizens can be encouraged to participate in the decision-making process with the crowdsourcing approaches in order to use the wisdom of the crowd effectively. Knowledge about human density and mobility patterns is the key element toward efficient urban development [35]. In this sense, a new concept — cyber-physical social systems (CPSSs) [36], [37], [38] has been proposed along with CPSs in which citizens are being maintained in the loop of smart system development and enhancement as sensors and/or actuators. CPSSs particularly aim to develop human-centric systems serving real-time autonomous decision-forming purposes and anticipating future trends and social dynamics/patterns in real-time by engagement with other users. Such systems consist of not only cyberspace and physical space but also human knowledge, mental capabilities, and sociocultural elements [36].

SCs should have the tools to enable citizens to know what is happening, when it is happening and how it affects citizens, tourists, companies and city administrators [5] about social activities, parking spaces, crime, traffic congestion, traffic accidents, better driving directions, pollution levels, emergency concerns (e.g., flood, earthquake, strong wind), directions for the closest gathering spots under any emergency situations based on the individual smartphone locations, areas to be avoided and so on. There are several attempts to fill this big gap such as ImproveMyCity crowdsourcing platform,[10] Ushahidi crowd-mapping platform.[11]

[10]https://www.improve-my-city.com/

[11]http://civicinnovationni.org/tools-directory/

To summarise, citizen engagement is generally not seen as a critical part of the improvement process and SC initiatives make little or no attempt to gain insight or collect subjective information from humans [25]. Effective and efficient human-based data collection, intervention and decision-making should be the main driving force of SC, essentially to quickly identify the requirements of residents and cities, to meet urgent input requirements of low-latency real-time application via crowdsourcing and consequently to support proper urban development in various aspects benefiting citizens and the sustainability of cities.

4) ENGAGEMENT WITH GLOBAL TECHNOLOGY COMPANIES

There is no single company to develop the "best SC" itself and SC development necessitates the collaboration of several companies specialised in developing a variety of the SC elements such as IBM, Intel, Cisco. Cities should have a common vision and mission, and clear directions that technology companies have to follow while developing SCs. More explicitly, companies should be directed to develop what the particular requirements of a city are, in other words, things should not be dictated by those companies where the needs of every and each city are differentiated from the others as explained throughout this paper.

B. ENGAGEMENT WITH EVOLVING TECHNOLOGIES, APPROACHES, AND INTEGRATION WITH EXISTING SYSTEMS

The infrastructure involving network, hardware, and software is the essential component on which SCs can prosper. The network infrastructure supports smart citywide applications. Health monitoring of all this infrastructure involving device status monitoring and data quality monitoring is a continuous process with intelligent autonomous diagnosis, prognosis, self-healing mechanisms, and desired actuation abilities. The SC platform for Amsterdam started in 2007 with the infrastructure development of telecommunication networks, and the smart energy (sEnergy) in Amsterdam has been a good example for other similar SC platforms as showing a strategic roadmap to forging technology to improve the lives of residents within public-private partnerships and engagement of citizens. Successful real-world engagement examples with technology, approaches, and integration with existing systems are presented in Table 2. Fig. 2 illustrates the infrastructure of the proposed framework — TCitySmartF. Its main layers enabling proper sensing and appropriate autonomous actuation are i) establishment of communication infrastructure for all the stakeholders, ii) edge IoT devices and citizens to collect data and interact with environment intelligently by harnessing large amounts of near-real-time data using sophisticated communication technologies, iii) edge/fog platforms, iv) the cloud platform involving cloudlets, and v) establishment of communication infrastructure for the integration of the domains not only within SC but also with the national

[12]https://international.stockholm.se/city-development/the-smart-city/

TABLE 2. Successful IoT and WSN engagement initiatives along with network infrastructure in SC development projects.

IoT and Infrastructure	Objective	City
Citywide IoT infrastructure (Intel)	to monitor and detect city environmental parameters [39]	Dublin
Sensors over major roads (IBM)	to collect traffic data [39]	Dublin
Supertrees	to collect environmental data including air quality, temperature and rainfall [40]	Singapore
A network of traffic sensors and GPS enabled devices embedded in taxicabs	to track city traffic and predict future traffic congestion [40]	Singapore
Traffic sensors across major roads	to monitor traffic [5]	Aarhus
Luminosity sensors in public buses	to monitor the quality of street lighting, all light poles on routes [41]	Rio de Janeiro
Pollution sensors installed in cars	to monitor the quality of air [42]	Oakland
Gas detection sensors installed in cars	to detect gas leaks [43]	Boston
Noise sensors	to monitor the level of noise in various locations (e.g., in buses) [41]	Numerous
Sensors on industrial bins	to inform the council when the bins are ready for collection [11]	Milton Keynes
Environmental sensors involving cameras	to collect information about the daylight for smart street lighting [15]	Amsterdam
Sensors placed throughout the grid	to monitor activity, current, voltage, and maintenance requirements in order to improve the reliability of the network and grid's ability [15]	Amsterdam
Microwave sensors, E-Z Pass readers, Advanced Traffic Controllers (ATSCs)	to detect congestions and be able to adjust the traffic lights remotely [44]	Midtown
Bluetooth enabled smart wearable device	to collect information about movements, walking distance, sleep patterns, unusual activities such as falling or activating a panic button from elder people [45]	Saensuk
Motion sensors (e.g., piezoelectric sensors) and brightness sensors	to collect pedestrian movement, vehicles movement and the amount of ambient light in the surrounding environment to determine a street light actuation on or off [46]	Numerous
Magnetic sensors, inductive loops	to monitor traffic within a wireless network	Numerous
WSN-based monitoring systems	to route the traffic and parking enabling road safety, to detect overspeeding, to establish an intelligent traffic signal control system [47]	Numerous
WSN-based parking systems	to find available parking spaces and direct the drivers to the most suitable ones with navigational information using WSN and parking meters in various cities [48]	Numerous
IoT-enabled infrastructure	to help develop smart applications based on the distributed IoT devices in order to improve the efficacy of city management and local businesses, improving the quality of human lives using a cloud-based infrastructure enabling safety services for children/elderly, drone-based smart marine, smart parking, crosswalk, and energy usage [20]	Busan
20,000 smart IoT devices	to perform several intelligent tasks such as measurement of temperature, humidity, speed and position of vehicles, traffic intensity, public transportation conditions, air quality, and water networks, parking space monitoring, garbage collection optimization [20]	Santander
300,000 smart IoT devices	to support smart grid operations in order to reduce energy waste [20]	Chicago
1000 sensors deployed across the city	to create an infrastructure for companies and start-ups to test and commercialise new applications in a real city environment [11]	Milton Keynes
400 smart lampposts	to collect real-time city data such as those concerning traffic, weather, and air quality and perform real-time data analytics to enhance traffic and city management through the smart sensors and cameras integrated with these smart lampposts [49]	Hong Kong
1200 traffic detectors, communication infrastructure	to visualise the real-time traffic at all strategic routes and major roads through a mobile app and website, as well as open data via the PSI portal. This infrastructure also provides free Wi-Fi and facilitate installation of 5G mobile base stations by telecom operators [49]	Hong Kong
Communication infrastructure	to enable better city services in terms of quick response, optical fibre is deployed that covers 325 km [50]	Barcelona
Communication infrastructure	to meet the initiation objectives and ensure high-speed mobile Internet access to residents with Motorola's 802.11n mesh wide area network (MWAN) [50]	Stratford
Communication infrastructure	to connect vehicles to each other, to deliver Internet access to people in and around vehicles and to connect the vehicles to the wired infrastructure of heterogeneous network providers and cloud by deploying a city-scale vehicular network that was based on existing fibre and Wi-Fi infrastructure [50]	Porto
Communication infrastructure	to provide 5G deployment infrastructure for developing smart applications [1]	UAE
Communication infrastructure	to accelerate the country's economic growth by providing inexpensive, superfast broadband access to 24 million citizens from virtually anywhere within the city limits [23]	Seoul
Communication infrastructure	to build a competition-neutral infrastructure (fiber network) capable of connecting all the city and meeting future communication needs, spur economic activity[12]	Stockholm
Communication infrastructure	to allow passengers free Internet access with 1,800 buses equipped with 4G network transmitters that interact with 52 base stations along the bus lines [13]	Nanjing
Communication infrastructure	to provide a wide-area network of computers to link and offer citizens and businesses various digital services. For example, individual apartments feature panels in each room that control lighting, temperature, and access to media; 20,000 residential units will feature telepresence technology [23]	Songdo

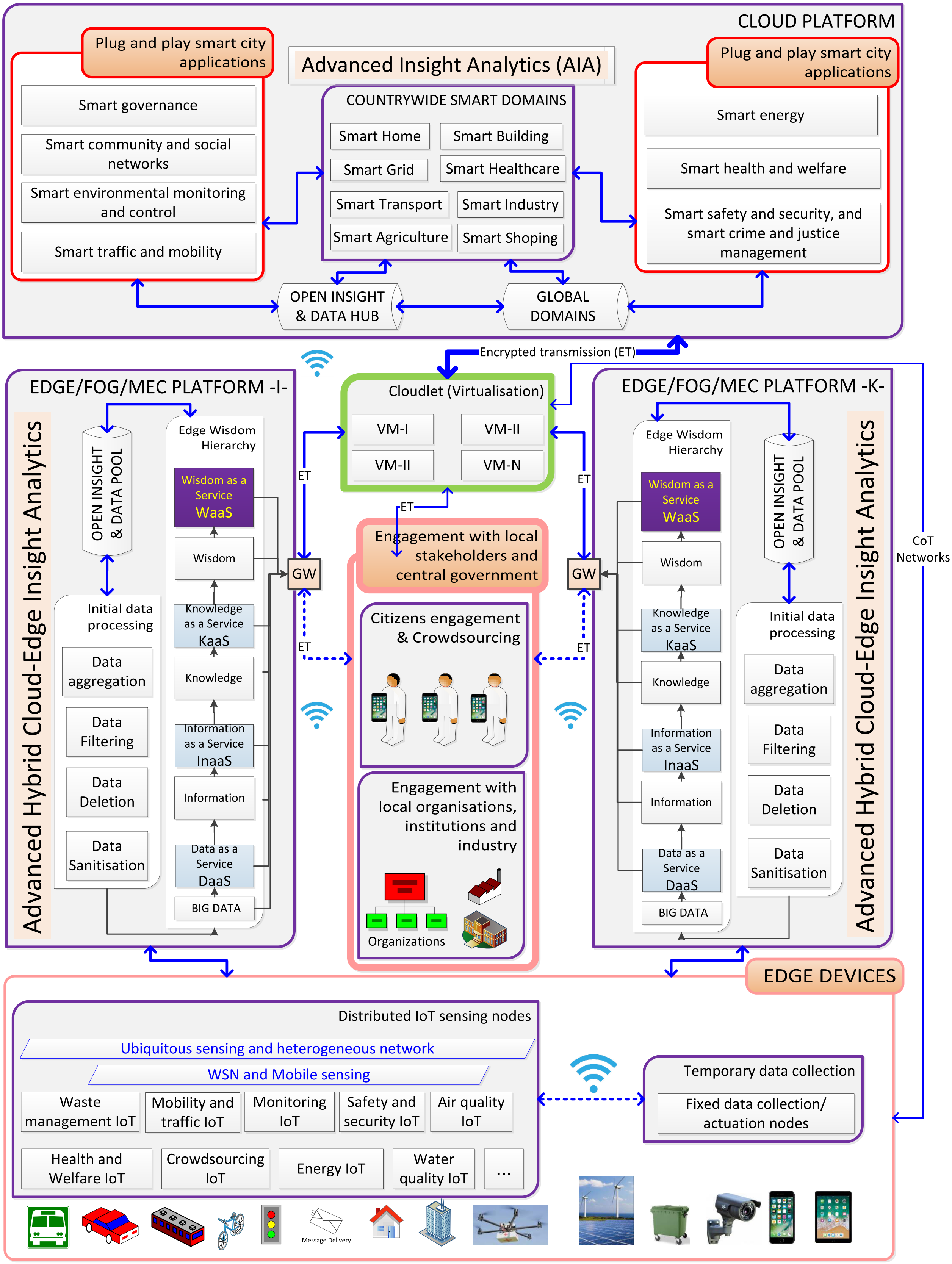

FIGURE 2. TCitySmartF architectural design framework: Main components of TCitySmartF and their interaction with each other.

and global domains. The functions of these layers along with the integration and engagement requirements with the technology elements are explained in the following subsections.

1) INTEGRATION WITH EXISTING SYSTEMS

Every and each city embraces a variety of characteristics of being smart with its various current smart applications and domains. In this manner, SC development initiatives could benefit from these domains substantially with effective integration. Some of these benefits can be summarised as i) exploring the previous experiences and best practices, ii) not repeating the same task over and over again, iii) reducing the cost, and iv) realising the objectives earlier than expected. Therefore, analysis of current domains in addition to the communication infrastructure on which SC thrives helps specify the desired real requirements.

2) ENGAGEMENT WITH EDGE/FOG AND CLOUD PLATFORMS

The cloud platform with vertically expandable data storage and processing capabilities has the advantages for massive storage, heavy-duty computation, global coordination and wide-area connectivity [51], while edge/fog, particularly mobile-edge computing (MEC) is useful for real-time operations and responses, rapid innovation, user-centric services, and edge resource pooling [52]. The cloud is approaching the edge and users as the massive network in a wider infrastructure with the deployment of multiple virtual machines (VMs) through virtualisation is being constructed by the leading cloud service providers [53], in particular, using the smaller versions of the cloud platform — cloudlets, which enable reduced latency. By leveraging low-latency offload, cloudlets using hypervisors servers enable a new class of real-time cognitive assistive applications on mobile cloud convergence [54] by massive virtualisation [55]. The advanced abilities of i) automatic detection of compromised accounts, malware, data breaches, and malicious insiders, and ii) reducing the risk of data loss using redundancy, archiving, VM backups at multiple locations make the platform very appealing to SC managers and governors with reasonable cost considerations.

Typically, IoT devices have limited processing and storage capabilities, while SC collects and analyses a large amount of data. Thus, a solution to store and process the collected data is to use a mixture of the cloud and fog computing infrastructure with load balancing abilities. Data collected either from IoT devices or users is aggregated, sanitised, filtered, processed for insight generation and compressed in the edge/fog to be sent to the cloud, reducing the network traffic, and computation and storage costs in the cloud. Data generated by the IoT edge devices using mobile sensing and WSN along with time stamp and geographic coordinates of each data is first sent to fixed nodes installed at strategic spots (i.e., temporary data collection nodes in Fig. 2) around the city, such as bus stops to be processed further in the edge/fog platforms. Edge (or fog) or most recent popular platform, so-called MEC is an emergent architecture for computing, storage, control, and networking that distributes these services closer to end-users [52] to enable a more independent processing and organisation, particularly for the applications requiring real-time decision-making, low latency, ultralow latency, high privacy and security with mobile services. In order to enable low-latency and increase efficiency further, multiple edge/fog/MEC nodes may be needed to support highly distributed devices and systems over large geographic areas as illustrated in Fig. 2 (i.e., MEC platforms 1-k).

3) ENGAGEMENT WITH IOT, AMSS, WSN AND MOBILE SENSING

IoT devices and AMSs [8] with resource constraint characteristics within IoE and AoE are composed of physical objects embedded with electronics, software, and sensors, which i) allows objects to be sensed and controlled remotely across the existing network infrastructure, ii) facilitates direct integration between the physical world and computer communication networks, and iii) significantly contributes to enhanced efficiency, accuracy, and economic benefits [56]. The large deployment of IoT is actually enabling SC initiatives all over the world [12]. With IoT and AMSs, physical objects are seamlessly integrated globally so that the physical objects can interact with each other and to cyber-agents in order to achieve mission-critical objectives [57]. WSN enabling the collection of data from a countless number of sensors is the main building block in establishing effective SC applications.

IoT paradigm can be used to collect the data of interest for each SC application using the sensing capabilities of everyday objects [41]. IoT ecosystems play a vital role to gather rich sources of information and different cities have already deployed IoT infrastructures and a variety of sensory devices to collect continuous data [5]. The emergence of IoT has led to increasing data volumes [58], which reached 44 zettabytes in 2019 [59] accounting for 10% of the total digital universe [60]. IoT devices are becoming even more powerful and can perform relevant storage and computation tasks on-site; thus, merging IoT, edge, and cloud resources and services as illustrated in Fig. 2 can bring unexpected solutions to the problems with a high level of effectiveness and responsiveness. There are many examples of applications by which the collected data from IoT devices and citizens is sent to the cloud platform directly to be processed without using the edge/fog platform, particularly within an interaction with the cloudlets. Iot devices directly connected to the cloud are labelled as Cloud of Things (CoT) [61]. This approach can be utilised for delay-tolerant applications and the applications not requiring privacy and security priorities. However, it is not advantageous for applications requiring low-latency and ultralow-latency actuation such as intelligent transportation systems (ITSs).

4) ENGAGEMENT WITH EVOLVING COMMUNICATION TECHNOLOGIES

The connectivity of the SC objects relies on different types of networks and communication technologies to perform collaborative tasks for making the lives of the inhabitants more comfortable [50]. Heterogeneous networks integrating cellular networks, wireless local area networks (WLANs), wide area networks (WAN), wireless personal area network (WPAN), wireless metropolitan area network (WMAN) are the backbone of SC and aim to provide a wide variety of connectivity services with a seamless communication between the physical and cyber world in a highly interconnected smart public infrastructures and services. The IoT devices spanning several kilometres are integrated using IPv6 addressing, particularly via low-power wireless personal area network — 6LowPAN. Several wireless low-powered WAN — LPWAN technologies such as LoRa ultra-narrowband (UNB) with an urban range of 2-5 km and SigFox with an urban range of 3-10 km support IoT deployments [12] along with 3G/4G, millimeter-wave communications, ZigBee (10-20 m), Wi-Fi (100 m) or Bluetooth (1-100 m), Z-Wave (100 m), WiMax (50 km), LTE (30 km), LTE-A (30 km) using small cell technology and Visible Light Communication (VLC). Public Wi-Fi supports the real-time SC applications in a crowdsourcing way, particularly, using location-aware services.

The utilisation of the existing communication technologies cannot provide error-free connectivity in SCs because these technologies are designed only for a limited number of devices and supported for a specific range of communication [50] and SC requires a well-designed network architecture to make the communication seamless. We envision that the integration of fifth-generation (5G) into SCs enabling high speed, high capacity, high reliability, and availability will address a number of the communication concerns in SCs. Readers are referred to [62] for the opportunities with the integration of 5G, IoT, and D2D in SCs.

5) ENGAGEMENT WITH ADVANCED INSIGHT ANALYTICS (AIA)

Various application approaches specific to SC have recently been proposed to manage the integration of all data in SC for better decision-making and control such as software-defined IoT (SD-IoT) architecture [63]. In SC, data is gathered from thousands of sensors and consequently, the created BD with a broader scale and scope is supposed to be analysed for insights needed to be shared among the services in a timely manner. In this context, AIA [8] running on BD is the key enabler in SC offering more tailored services to residents as explained by the Chief Technology Officer of Amsterdam — ''What we see right now is that it is not about installing as many sensors as possible, but rather about creating the right algorithm to do the proper analytics'' [15]. Analytics is the science of using data to build models that lead to better decisions that in turn add value to individuals, companies, and institutions [64].

More and more sensors and devices are being interconnected via IoT techniques, and these sensors and devices will generate massive data and demand further processing, providing intelligence to both service providers and users [65]. BD increases the chance of representing the real world and consequently extracting better insights for better decision-making. Erroneous and noisy data is cleaned, and unnecessary/unuseful data is filtered out by Advanced Hybrid Cloud-Edge Insight Analytics in the fog platform in such a way that useful raw data that may result in insights is not discarded as illustrated in Fig. 2 to both clean and reduce the amount of BD significantly into highly summarized forms before placing in the cloud platform. In this way, a huge amount of memory space, storage and processing time is saved. With the support of BD analytics, all the stakeholders and advanced devices can be connected to each other in IoE and AoE environment intelligently via autonomous machine-to-machine (M2M), Peer-to-Peer (P2P) communication to be able to work as an integral part of bigger systems. Bigger synergies using location-independent monitoring, control and actuation mechanisms are generated in order to build cutting-edge advanced smart systems. Moreover, AIA with its decision support capability provides critical information such as historical reports, statistical analyses, time-series comparison, forecasting business opportunities and executive summaries to managers and executives to facilitate better decision-making [66]. Furthermore, it produces and delivers insights to be used as an input into other systems or merged with other insights created locally or globally for better working IoT and AMSs to support autonomous and dynamic real-time decisions. Future algorithmic governance for SC needs to be inherently distributed and mobile. The programming for SCs requires a much-sophisticated understanding than currently used for distributed programming [67] even though highly mobile and distributed sensing and actuation has been recently well-incorporated into the SC domains.

A voluminous data is created in the SC domains. The IoT infrastructures along with citizen engagement act as a major source of continuous data collection and the enormous amount of data can be harnessed by many SC applications [5]. Several platforms such as iCity, Smart Santandler, OpenIoT, iCore, SpitFire, PLAY, IBM's Star City, VITAL and City-Pulse have been developed to integrate real-time data and present insights obtained from the analysis of integrated data to meet the citizens' instant and future needs [5]. For instance, future traffic flow can be predicted using analytics running on traffic information and future plans along with instant best possible directions of vehicles can be determined to mitigate various traffic bottlenecks. Readers are referred to [68] for the specific machine intelligence algorithms employed in SCs with examples. The main real-world SC domains in which BD analytics plays a huge role are presented in Tables 3 and 4 and explained in the following section.

C. MAIN SMART DOMAINS IN SC

The main SC domains involving their sub-domains are classified in the framework — TCitySmartF (Fig. 1) based

[13] http://futurecity.glasgow.gov.uk/ops-data/
[14] http://www.laexpresspark.org/about-la-expresspark/
[15] http://www.hubcab.org/#13.00/40.7219/-73.9484

TABLE 3. Successful smart applications in smart city development projects -I-.

Application	Objective	City
sGovernment	to monitor city from operation centre in which Public Space CCTV, security for the city council's museums and art galleries, Traffic Management and Police Intelligence are brought together [13]	Glasgow
sGovernment	to cut the city's spending and make the residents contact the council 24/7 with smart online apps [11]	Stockholm
sGovernment	to establish an advanced and transparent e-government — the online disclosure of all bids for government contracts has significantly reduced corruption [23]	Seoul
sGovernment	to help manage all aspects of urban life, from traffic control to water and energy use to recycling with a green, state-of-the-art datacentre [23]	Songdo
sGovernment	to provide services to citizens in order to engage in government services [1]	Dubai
sEnvironmentMonitor, sGovernment	to serve a waste collection model based on IoT in order to help the government better use the information produced, and finally achieve the goal of intelligent cycle [69]	Wuhan
sEnvironmentMonitor, sGovernment	to minimise the sum of the collection costs for solid waste recycling by optimizing the routes for each truck integrated with GIS and determining the quantity of the collected materials [70]	Cogoleto
sEnvironmentMonitor, sGovernment	to predict the quantity and diversity of solid waste with intelligent and sensorised (e.g, ultrasonic distance sensor, camera, LED) bins in order to determine the quality and quantity of the waste in the container [71]	Shanghai
sEnvironmentMonitor, sGovernment	to manage all the processes involving waste loading and transportation in pneumatic pipes from depots to dumps using Ubiquitous Sensor Network (USN) and IoT Technology [71]	Seoul
sEnvironmentMonitor, sGovernment	to reduce the waste of water with the installation of smart meters on the water pipelines, which led to early detection of leaks, which in turn resulted in 12% reduction in water consumption [72]	Kalgoorlie-Boulder
sEnvironmentMonitor	to monitor the air quality using the deployment of air sensors in moving cars [73]	Antwerp
sEnvironmentMonitor	to monitor temperature and humidity intelligently using IoT devices [20]	Santander
sEnvironmentMonitor	to monitor water intelligently using IoT devices in order to provide healthy water to the residents [20]	Milton Keynes
sEnvironmentMonitor	to monitor water/weather with IBM IoT devices in New York, Chicago, Kansas, Atlanta, Miami [74]	Numerous
sEnvironmentMonitor	to monitor a set of environmental parameters over a large area as well as to provide additional information for the end-user like the location of the buses and estimated arrival times to bus stops by utilising public transportation vehicles [75]	Belgrade
sEnvironmentMonitor	to achieve sustainable management of the traffic by using a pervasive air-quality sensors network as well as prediction models [76]	Salamanca
sEnvironmentMonitor	to build an early warning system for detecting river flood using smart metering and forest fire using temperature, humidity and CO_2 sensors [77]	La Garrotxa
sTrafficMobility	to monitor and control traffic and reduce CO_2 emission [11]. This has resulted in 20% less traffic, 12% drop in emissions and a reported 40,000 additional daily users of public transport [74]	Stockholm
sTrafficMobility	to reduce the congestions at the junctions using various sensing abilities by providing the traffic engineers with the ability to quickly identify and respond in real-time to traffic conditions [44]	Midtown
sTrafficMobility	to improve climate and traffic using cameras, drivers' mobile devices and GPS [78]	Boston
sTrafficMobility	to identify congestion spots and traffic patterns to improve the traffic using crowdsourcing via the Waze [22]	Louisville
sTrafficMobility	to collect real-time occupancy information from buses operating on different routes [12]	Madrid
sTrafficMobility	to deliver an efficient traffic system within effective monitoring [20] in addition to managing the city's 20,000 surface parking spaces [11] in order to control carbon emissions and support of sustainable growth without deploying additional infrastructure by collecting data from several deployed smart devices [20]	Milton Keynes
sTrafficMobility	to enable residents to access parking information and pay parking fees via a smartphone app based on predictive modelling-based using the system that keeps track of how many have paid and for which time periods rather than solely dependent on sensors [15]	Amsterdam
sTrafficMobility	to detect roadside parking spaces by placing mobile sensing systems on vehicles such as buses, taxis or private cars to continually gather data as they travel along their routes [79]	Surrey
sTrafficMobility	to monitor and manage traffic intelligently by enabling capabilities of predicting imminent congestion using cameras, GPS devices, and a network of sensors are deployed on taxicabs [50]	Singapore
sTrafficMobility	to monitor and manage public transport intelligently by connecting the different types of vehicles that provide transportation for passengers, a multi-network-onboard unit (OBU) equipped with Wi-Fi/DSRC/cellular interfaces, called NetRider was developed [50]	Porto
sTrafficMobility	to alert drivers to empty parking spaces, which can be seen on maps via smartphones from which citizens can pay the fee as well [74]	San Francisco
sTrafficMobility	to implement a system that automatically charges drivers a fee based on how much they drive using control points outfitted with lasers and cameras to reduce congestion and greenhouse gas emissions [23]	Stockholm
sTrafficMobility	to manage city traffic and mobility, particularly, to dynamically adjust the traffic signal priorities at intersections in order to ease congestion based on traffic volume using cameras, free, citywide, open Wi-Fi network with 1,300 access points, a network of inductive loop detectors for counting cars [80]	Oulu
sTrafficMobility	to allow the parking enforcement officers to scan parked vehicles from their moving cars or scooters at a rate of 1,250 scans per hour. The information about the vehicle with no parking permit validity is forwarded to the on-street parking attendants with Sigamax hand-held computers, to issue enforcement notices [10]	Amsterdam
sTrafficMobility	to locate and guide drivers to car park spaces available with a platform based on a network of wireless sensors capable of detecting unoccupied spaces outdoors, and on an alternative positioning system with more precision in urban areas than GPS technology [81]	Barcelona
sTrafficMobility	to reduce traffic congestion and air pollution by encouraging use of alternative modes of transportation with Express Park smartphone app showing available spaces using demand-based pricing by which rates are low when demand for parking is low, and it increases when demand is high [14]	Los Angeles

TABLE 4. Successful smart applications in smart city development projects -II-.

Application domain	Objective	City
sTrafficMobility	to reduce traffic congestion and air pollution, and fight gridlock by synchronisation of traffic lights in order to make the traffic move seamlessly using cameras and many other sensors [82]	Los Angeles
sTrafficMobility	to reduce traffic congestion and air pollution using an intelligent parking system in which 10,000 sensors connected to nearby multi-service parking meters are installed in 13 different parking areas and drivers can check parking availability with a smartphone app [48]	Nice
sTrafficMobility	to find new ways of public transportation (e.g., potential of taxi shareability) by investigating collective mobility and travel patterns — how and when taxis pick up or drop off individuals, and zones of condensed pickup and drop-off activities using HubCap system mounted in taxis leading to less congestion, less polluted, cleaner environment [15]	New York
sTrafficMobility	to reduce the number of vehicles circulating in search of parking spaces by assisting motorists in finding real-time vacant parking spaces using on-street parking meters which accept payment of parking fees through multiple means, including remote payment via mobile app [49]	Hong Kong
sTrafficMobility	to build smart work collaboration centres to bring people together and create collaborative synergies, usage of office space that has decreased, despite a 7% increase in employment. While this has had a positive impact on traffic levels and energy usage, it has negatively impacted the owners of office buildings and associated businesses [15]	Amsterdam
sTrafficMobility	to facilitate disabled people, RFID cards are used to extend crossing times when tapped against traffic light poles [50]	Singapore
sEnergy	to increase energy efficiency and reduce costs in public buildings with smart heating and lights [11]	Stockholm
sEnergy	to illuminate only when sensors detect the presence of an individual with smart street lighting [12]	Fujisawa
sEnergy	to reduce energy consumption by installation lamp posts equipped with cameras, environmental sensors, Wi-Fi [83]	Amsterdam
sEnergy	to increase the efficiency of lighting with Green Vision project by deploying a control and management system on LED lights that can be programmed to monitor, optimise and report energy consumption and malfunctions [84]	San Jose
sEnergy	to develop a Virtual Power Plant for energy management and monitoring. Using load distribution, the city is able to provide load balancing and support new services [83]	Rheintal
sEnergy	to develop and demonstrate new approaches to city heating and electricity supply for the city to provide ancillary services to the electricity grid, in order to support the goal of reducing CO_2 by 40% by incorporating buildings with demand-side management, combined heating, and power plants (CHPs) and thermal storage systems [85]	Hamburg
sEnergy	to develop a city with low-carbon using hierarchical energy management systems (EMS), sensitive photovoltaic (PV) generation with YSCP SC Project supported by Tokyo Institute of Technology, Toshiba, Mitsubishi, and Hitachi [86]	Yokohama
sEnergy	to provide efficient use of lighting and to reduce the cost of water management by implementing remote water metering with SLICENET project supported by 5G infrastructure [73]	Alba Iulia
sEnergy	to draw information relevant to how the city functions, including data from key infrastructure networks (energy, transport and water) and sensor networks such as weather and pollution data; satellite data and data from social media and specialised applications using smart data hub [11]	Milton Keynes
sEnergy	to create electricity, provide hot and cold water and power air-conditioning for some of the city's most prominent buildings with Combined Heat and Power Programme [11]	Birmingham
sEnergy	to manage three key areas: smart energy, smart transport, and smart data which are connected to smart grid to help the city meet its target of reducing CO_2 emissions by 40% with the Green ICT project [11]	Bristol
sEnergy	to be able to determine how to reduce electricity usage with a program of smart metering with the aim of facing new energy conservation regulations and stimulating economic growth [50]	Stratford
sEnergy	to reduce carbon dioxide emissions by integrating electric vehicles into the local power grid, which relies heavily on renewable wind power involving a network of public and personal charging stations and integrated technologies to manage the charging as well as load balancing and billing [23]	Bornholm
sSocialCommunity	to incentivise the use of public transit by providing online information to drivers about insurance discounts, reduced-cost parking, a tax break for leaving their cars at home one business day, and a week using citywide Internet [23]	Seoul
sHealthWelfare	to monitor elder people via a small Bluetooth enabled smart wearable device by collecting their movements, walking distance, sleep patterns, unusual activities such as falling or activating a panic button, and consequently improve the quality of care for these people. The collected information is aggregated and analysed and gained insights are sent to the municipal nursing headquarters cloud system to actuate proper actions [45]	Saensuk
sHealthWelfare	to increase the quality of emergency medical services using IoT devices by transmuting the video images of patients in ambulances, facilitating information sharing between the rescue crew and the doctors at the hospitals in real-time using tablet devices and Internet Protocol cameras placed in ambulances [21]	Yokosuka
sHealthWelfare	to connect ambulances equipped with 4G network transmitters to hospitals so that paramedics can conduct remote consultations as soon as patients enter the vehicle [13]	Nanjing
sSafetySecurity	to provide emergency alert, reduced crime within effective monitoring and actuation mechanisms equipped with IoT and WSN distributed all around the city [20]	Chicago
sSafetySecurity	to help the city to prepare for and respond to flood-related incidents and a process management system through which multiple agencies can make coordinated and intelligent decisions based on dynamic data from weather sensors, video surveillance and field personnel overlaid on a comprehensive geographic information system (GIS) [23]	Rio de Janeiro
sSafetySecurity	to keep the citizens safe and dry by detecting floods using IoT devices where large parts of the city are below sea level [21]	Amsterdam
sSafetySecurity	to increase the safety and security of citizens by connecting personnel, systems, and applications across diverse organisations to help improve situational awareness with fast, effective integrated services supported by high technologies. Giving officers the ability to quickly communicate and retrieve data, images, and forms helps them make accurate decisions and work safely in the field by protecting the well-being of the community [87]	Charleston
sSafetySecurity	to warn residents of approaching storms and floods with the street lights flashing red [88]	Eindhoven

TABLE 5. Future plans in developing smarter cities.

Application area	Future objectives	City
Smart operations centre	to monitor and control the new intelligent CCTV networks intelligently for better safety and crime/terrorism prevention [11]	Glasgow
Smart active travel	to make the city more cyclist- and pedestrian-friendly to cut traffic and carbon emissions [11]	Glasgow
Smart social transport	to minimise route duplication and reduce unnecessary journeys by exploring the use of route optimisation software and scheduling tools [11]	Glasgow
Smart traffic with AVs	to enable the use of AVs actively without putting the safety of others at heightened risk with dedicated tracks, known as PRT (personal rapid transport) that is currently under construction [10]	Masdar
Smart street lighting	to collect data such as footfall, air and noise pollution levels by installation of energy-efficient LED lamps and sensors [11]	Glasgow
Smart street lighting	to enables remote lighting management and control with 20,000 networked streetlights, leading to improved energy efficiency, lower operational costs, and enhanced public safety [89]	Glasgow
sEnergy	to map the 2D & 3D energy consumption of residents and businesses across the city with an app by which users will be able to enter information relating to their property, run a simulation to calculate the anticipated energy consumption of their property along with the actual energy use with the privacy-preserving ability [16]	Glasgow
sHealthWelfare	to provide remote home healthcare for elder people, children, and medication management via HD videos streaming integrated with the healthcare system in order to facilitate community care by clinical staff, and allows multiple staff members to simultaneously discuss professional care [16]	Taiwan
Smart City Strategy	to expand the international competitiveness, increase the resource efficiency and climate neutrality, and create a pilot market for innovative applications in order to make the city more efficient, healthier, more sustainable, more liveable and cleaner along with climate protection, resource conservation and sustainability [90]	Berlin
Connected Smart City	to transform the city into SC with the deployment of smart street lighting, smart traffic system to optimise traffic flows and detect incidents earlier, environment and infrastructure sensing [15]	Berlin
Communication infrastructure	to provide 5G communication services and credentials during the Commonwealth Games in 2022 with Urban Connected Community project. This platform will use data models to describe urban life, and these will mature into the 2030s to support physical facets: traffic lights; sewage works; air quality measures, and Virtual citizen services solution, where administrative services are provided through a high-definition, remote video kiosk [1]	West Midland
Communication infrastructure	to provide the world's first city-scale demonstration of a programmable city using software-defined network by connecting different facets of the city in a fibre and wireless network. This will serve different digital ecosystems with different service qualities on demand, which will be a game-changer for SCs, as it will provide the autonomic flexibility required to enable the city as a data platform to emerge [1]	Bristol

on an analysis of the recent SC development initiatives with the successful use cases, future SC development plans, and many other particular SC development solutions. The sub-domains of these domains are expandable with respect to future technological improvements. For instance, fully driverless vehicles on roads in the future will impact sTrafficMobility domain and a new sub-domain may need to be incorporated into this domain such as ''smart management of fully driverless vehicles''. The main domains are shown in Tables 3 and 4 with their real-world implementations. The future plans of various SC development initiatives are presented in Table 5. Furthermore, particular SC application solutions are displayed in Table 6. The SC domains, the nationwide agreed-upon sDomains, and their interrelation are illustrated in Fig. 3. We would like to note that sTransportation is the subject of the smart country and sTrafficMobility integrated with sTransportation is analysed within SC in this paper. In a similar way, sIndustry, sHealthcare, sAgriculture, and sGrid are the main domains of the smart country. These sDomains should be planned statewide and nationwide as explained in Section II-D, and it may not be a good idea to squeeze these domains within SC. That's why, the ministries of education, transportation, energy, economy/commerce, healthcare, and agriculture have been established in many countries to specify, direct and dictate the required countrywise policies on these specific fields. Instead, in this paper, smart community and social networks (sSocialCommunity) integrated with sEducation, sEnergy integrated with sGrid, and smart health and welfare (sHealthWelfare) integrated with sHealthcare are analysed in SC. Additionally, sShopping, sHome, and sBuilding are also examined in the other domains in Section II-D for their unique ways of implementations by their users and leading companies. The inevitable interrelation of these sDomains is explored to emphasise the importance of integration for establishing synergistic implementations enabling optimised resource utilisation.

Mobile crowdsourcing (MCS) is known as a key emerging paradigm for enabling SCs, which integrates the wisdom of dynamic crowds with mobile devices to provide decentralised ubiquitous services and applications [34]. Data generated with MCS is used as an important dynamic input for developing most of the smart applications as explored in the following subsections.

1) SMART GOVERNMENT (SGOVERNMENT)

Efficient public services designed to meet citizens' different needs and desires are the driving forces of a thriving SC. The city's responsibility is to provide support and facilitate services in a 24/7 runtime environment. The main elements of sGovernment are i) establishing an effective intertwined

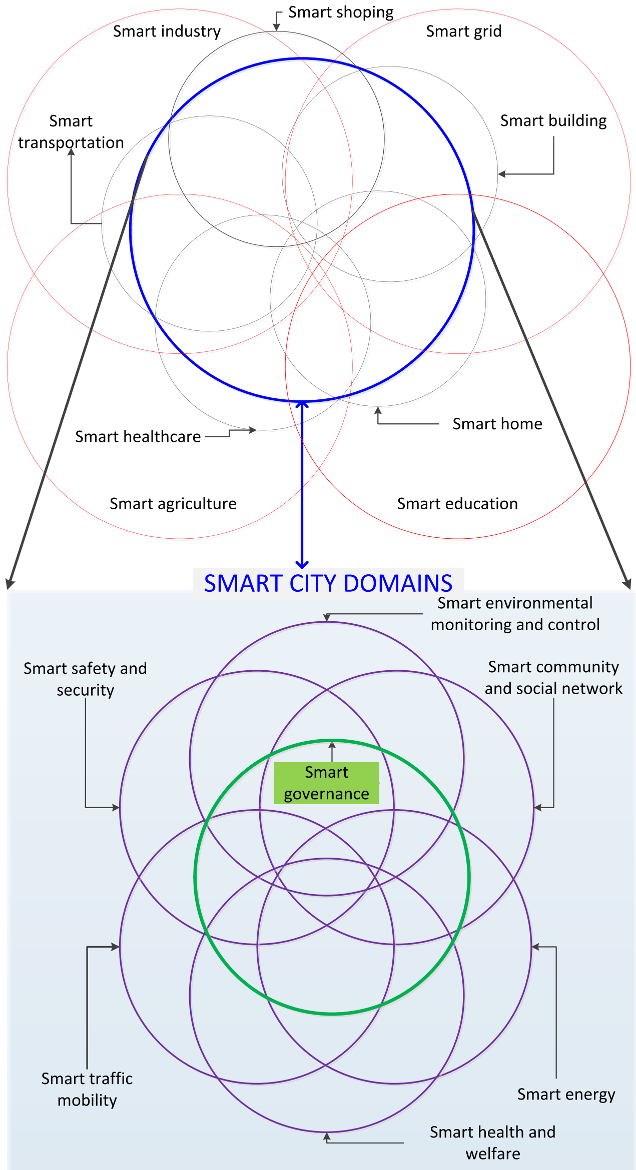

FIGURE 3. **TCitySmartF: Interaction of essential sDomains within SC (bottom) and with the countrywide sDomains (top).**

integration of all sDomains, ii) achieving an efficient coordination among all the city government departments along with the centre government via these integrated sDomains using intelligent decision-making abilities, iii) providing access to all information services through official government websites (e.g., e-services: applying for schools and elderly care, paying taxes and housing), iv) providing flexible smart communication applications to citizens for their effective engagement with the city government departments and interaction with SC, and v) providing information and giving early warnings and directions via the SC applications when something is wrong.

sGovernment can be provided with a larger set of capabilities equipped with sGovernment applications, sGovernment buildings, and insight-driven directions supported by distributed sensing, autonomous and semi-autonomous actuating devices with reliable and fault tolerance features. It aims to both decrease the costs of public services with optimised management mechanisms and make a city more transparent, impartial, e-democratic, and efficient through the use of real-time data and feedback. Effective integration of sGovernment with all the SC domains is necessary to enable the effective management of a city as illustrated in Fig. 3 with the green circle in the middle of the SC domains. Furthermore, strong integration with smart countrywide domains in a broader perspective is highly desirable for the effective management of a city as illustrated in Fig. 3. The SC initiatives aim to establish "smart operation centres" to perform sGovernment operations effectively by monitoring and controlling a city. Readers are referred to Table 3 for real-world implementations of "sGovernment".

2) SMART ENVIRONMENTAL MONITORING AND CONTROL (SENVIRONMENTMONITOR)

Loss of environmental quality is one of the biggest threats of our century to health and human well-being, together with environmental impacts [76]. Real-time detection of the events in the physical world such as air and water pollution, temperature, gas, CO_2 emission, noise, forest conditions, forest fires, floods is performed to observe the current and changing status of the environment using WSN or mobile sensing in a distributed network infrastructure. BD is processed in the cyber world with smart pervasive monitoring applications. Then, controlling mechanisms with location aware services using insights obtained from BD analysis are triggered to both increase citizens' awareness of their immediate environment and make cities sustainable places. For instance, smart management of water can ubiquitously detect harmful bacteria and pollutants in water and alert municipal authorities before spreading of diseases (e.g., using water turbidity sensors) [83]. Air pollution is another important emergency to be tackled effectively for citizens and is being monitored by many cities [42] since it is at alarming levels in many cities. The weather information, that is, temperature, humidity, wind direction, and pressure is acquired from several specialised IoT devices deployed in various parts of a city. Smart waste management (SWM) with extensive use of the IoT and WSN such as capacity, weight, temperature, humidity, pressure, and chemical sensors using RFID tags, camera technologies, GPS, GPRS, GIS is underway in many cities all around the world. The real-world waste management examples for SCs have been analysed in [91]. Intelligent waste containers can bring real benefits to citizens where they are able to indicate that they are getting full and must be emptied [12]. Citizens can check through a smartphone application if the waste containers in the street are full or not [12]. Readers are referred to Table 3 for real-world implementations of "sEnvironmentMonitor".

The monitored data is processed and shared by a large number of services within SC to provide decision-making

[16] http://futurecity.glasgow.gov.uk/energy/

abilities. For instance, SWM integrated with sTrafficMobility helps collect the waste efficiently without causing any congestion. Furthermore, the monitored data and gained insights in SC support the other countrywide and global sDomains as detailed in Section II-D. Insight sharing is prioritised based on the different requirements of end-users and nodes, particularly prioritising ultralow-latency and low-latency requirements.

3) SMART TRAFFIC AND MOBILITY (STRAFFICMOBILITY)

A city can not be labelled as SC without a reliable and efficient traffic and mobility system enabling unrestricted, faster, cleaner and cheaper mobility for people and goods based on travellers' preferences, and behaviours. With volumes of traffic and population constantly on the increase, a well-organised ''intelligent'' mobility system, is a cornerstone of urban life [10] to connect the different parts of a city together as hubs of mobility, to provide the most convenient and sustainable mobility options, and to reduce the level of road-induced stress. The main goal of sTrafficMobility is to monitor city dynamics and direct these dynamics in order to make a city life smoother and easier (e.g., optimal mobility, less congested, less polluted environment). The intelligent mobility and traffic system could enable us to calculate the best route in real-time by connecting different transport modes to save time and reduce carbon emissions [12]. The essential elements of sTrafficMobility are i) smart traffic management (e.g. traffic monitoring, routing, prediction and directions, smart traffic signals/lights), ii) smart public transportation with public transport networks involving a shared ride (e.g., shared taxis, flexible car sharing), iii) smart cycling (e.g., shared bikes), iv) intelligent parking, v) intelligent delivery (e.g., package delivery, fresh food delivery by trucks), vi) smart human mobility and commuting (e.g., elder, disabled people mobility) and pedestrian management (e.g., the flow of people), vii) smart autonomous driving supported by new hybrid and electric vehicles, and autonomous vehicles, viii) collision avoidance, ix) autonomous toll collection, and x) smart supply chain integrated with sIndustry and sShopping.

Defining smart mobility only in terms of the most advanced technological characteristics, without taking the human dimensions into account, won't be useful for the cities of tomorrow [105]. Therefore, the mobility requirements, particularly, human mobility, and vehicular traffic requirements along with all other dimensions should be considered hand in hand in planning and in developing smart mobility applications. The optimisation of mobility based on evolving mobility patterns (e.g., passenger volumes by various public services, taxi, bike; travel route, duration, intervals, displacement, distributions among services) within different days (e.g., public holidays), rush hours and times, or weather conditions are required to make the city dynamics flow seamlessly with effective decision-making abilities (e.g., congestion management, deploying new bus routes and stations, optimal use of the roads and parking spaces). Detecting and determining timely-manner mobility patterns requires the engagement with mobile crowdsourcing input and integration of all mobility services involving the information about private car use and driving habits, particularly to enable the optimisation of real-time mobility. The use of mobile crowdsourcing utilities and vehicle-to-vehicle (V2V) collaboration in driving helps real-time monitoring large urban regions efficiently. The reasons for steering the crowd might be for emergency evacuation, guided tours, safe movement of people during large rallies and concerts, regulating the use of spaces or for commercial purposes (e.g., steer crowds to move through certain businesses areas) [103]. Traffic signals play a critical role in mitigating traffic congestions and reducing the emission in metropolitan areas [106]. The optimisation of traffic signals can be provided to accommodate the intrinsic and complex city demands based on traffic patterns and instant dynamics that can be acquired from the integration of sDomains mentioned here with effective information exchange in real-time. For instance, no need to stop vehicle traffic on the roads on a regular basis if there is no pedestrian presence willing to cross the road. Limited parking spaces involving on-street parking spaces and mobility of vehicles to those spaces involving reservation abilities should be managed intelligently in order to shorten parking search time with less fuel consumption, reduced volume of vehicles cruising looking for parking space and less congestion leading to cost reduction and less pollution. The success of these systems and mobility systems lies in detecting the current location of the user and the current dynamics around the user with the help of effective crowdsourcing applications.

The optimisation of mobility should be performed to support the other sDomains, particularly, sEnergy, sHealthWelfare (e.g., use of bikes), sSafetySecurity, consequently in order to contribute to the final objective — sustainability, particularly with less fuel consumption and CO_2 emissions. In this context, the efficient flow of people and goods should be carried out using the vehicles with energy-efficient systems (e.g., electrical, solar, power/energy conversion). Smart bike-sharing systems (BSS) are very popular in modern cities [103]. Smart cycling to provide the mobility of citizens whilst still giving the vehicle owner the flexibility of using an internal combustion engine [107] has been well-adopted in various SCs all around the world enabling less energy consumption, less pollution, and healthier life. With RFID toll collection, drivers need not stop at a physical toll booth, which typically takes time, blocks traffic flow, causes pollution, and requires manpower for toll collection [99]. Another new and emerging service — flexible car sharing, available predominantly in big cities using smart mobility services such as Red Ride in the US, and Matchrider and Flinc in Germany helps users find the closest vehicles or shared rides available [105], which increases the mobility of people with flexible options (flexible places to collect and leave cars, choosing types such as economical cars). Mobility using these applications and approaches becomes more functional as the ''first mile/last mile'' (FMLM) problem is alleviated.

TABLE 6. More useful proposed solutions for various domains in developing smarter cities.

Application domain	Smart solutions
sEnvironmentMonitor	Places can be equipped with sensors to monitor environmental conditions; cyclists/runners can find the most healthy trips using real-time smartphone directions and the city can respond by adjusting the traffic or by planting more trees in some areas [12].
sEnvironmentMonitor	Collaborative UAVs equipped with sensors, IoT devices can be employed for many monitoring activities in cities for collecting real-time data successfully such as air pollution ([92]), weather conditions. Readers are referred to [93] for many other opportunistic use of UAVs in SCs.
sEnvironmentMonitor	Crowd-sensing inspired AirSense systems aimed at collecting and aggregating sensor data to monitor air pollution using air quality monitoring devices (AQMDs) with smartphones collaboratively perform sensing and data collection all around the city using the citizens‘ smartphones enabling citizens to make informed decisions on managing and improving the environment [94].
sSafetySecurity	Pervasive video surveillance in SC captures a tremendous number of images and videos, which may be utilised to infer local residents' trajectories to develop better public services based on the demands of residents.
sSafetySecurity	The mobile objects involving vehicles and residents can be tracked autonomously using cameras, GPS, etc. to prevent any likely crime or disasters.
sSafetySecurity	Once a criminal is reported to the control centre, the closest UAVs among available UAVs fly and arrive at the site of the criminal. Then, if the criminal is verified, a fleet of UAVs can be used for tracking a fugitive and collecting data including criminal identification [95].
sSafetySecurity	For emergent purposes, it is possible for UAVs to deliver first-aid treatment to accident locations. Also, when cars on land are in temporarily unreachable areas or remote places due to unexpected disasters, UAVs can deliver any necessary goods as well as take a role as temporal equipment to recover communication infrastructure [95].
sSafetySecurity	UAVs can contribute to minimizing the damage of a disaster by sending the recorded information to firefighters after a speedy arrival as well as by warning of the serious event to citizens in neighbouring areas or other areas [96].
sTrafficMobility	Road traffic can be adjusted by managing the traffic light and public transportation tools, such as buses, trains, and shared bicycles along with all other vehicles in the traffic [97].
sTrafficMobility	UAVs can be utilised for patrol among frequently congested intersections so that areas with traffic jams are controlled promptly by guidance signals or broadcasts of UAVs [95].
sTrafficMobility	Crowdsourcing real-time travellers‘ information (e.g., sensing information from smartphones or vehicles equipped with tracking devices) helps find better instant navigation routes [63].
sTrafficMobility	UAVs can be used to detect real-time on-street parking spaces, and based on the space information vehicles can be directed to the closest parking space in SCs.
sTrafficMobility	A road support team can be replaced or supported by a set of UAVs that could fly around the location of an incident to provide basic support, or at least to send back a survey report about the situation. Moreover, a traffic police officer can also be replaced or supported by UAVs, which can fly over vehicles on roads to monitor and report possible traffic violations. They can be equipped with speed cameras, dynamic traffic signals to perform further tasks. Additionally, UAVs can provide road users with efficient information [98].
sTrafficMobility	Autonomous vehicles can be efficiently used on dedicated roads or tracks in order not to cause a collision, by which they are separated from the vehicles used by humans [10].
sTrafficMobility	At Intertraffic 2016, Siemens demonstrated SiBike – a bicycle prioritisation system. The cyclist's GPS-connected smartphone sends a signal to the control centre the moment the bike passes a trigger point. The control centre then issues a command to give the cyclist a green traffic light. All trigger points are software-based [10].
sTrafficMobility	Systems enabling you to prebook and prepay for a parking space from your dashboard are under development (ParkNow) [10]).
sTrafficMobility	Use of smart apps in mobile phones to hire taxis and even track the exact location of the taxi and the driver's information [99].
sTrafficMobility	UAVs are going to be used immensely in delivering goods in long distances using optimised routes, which will both reduce the cost and gas emission substantially [100].
sTrafficMobility	Traffic lights should be switched on behalf of the pedestrians or vehicles automatically by sensing the vehicles in the traffic close to these lights and pedestrians waiting to cross.
sHealthWelfare	Traffic lights can be adjusted to give ways to the ambulances automatically using sTrafficMobility. Additionally, routes of ambulances may be shared with the vehicles in the same routes using sSocialCommunity and sTrafficMobility to help ambulances reach their destinations rapidly.
sHealthWelfare	Monitoring Parkinson disease and informing the registered doctor under emergency situations within SC [101].
sHealthWelfare	Patients with heart or respiratory problems could be directed with an optimal route by avoiding areas with high atmospheric pollution levels [102].
Smart crowdsourcing	The real-time dynamics of a city can be observed by incorporated more crowdsourcing application into SC the collaboration among the same type of crowds, such as vehicle-to-vehicle, pedestrian-to-pedestrian, bicycle-to-bicycle, and drone-to-drone. Actually, efficient collaboration among different types of crowds (e.g., vehicle-to-pedestrian, vehicle-to-bicycle, drone-to-vehicle, and so on) may enable more interesting applications as in a package delivery system using conventional trucks and UAVs [103].
Synergistic engagement with various sDomains	Load forecasting can be managed effectively in the electricity supply industry where it is crucial to determine future demand for power as far in advance as possible. If accurate estimates can be made for the maximum and minimum load for each hour, day, month, season, and year, utility companies can make significant economies in areas such as setting the operating reserve, maintenance scheduling, and fuel inventory management.
Communication infrastructure (UAV network)	Swarms of UAVs connected to several millilitre-wave (mmWave) base stations on the ground can be deployed to establish the communication with the IoT devices on the ground, particularly wherever the communication can not be established using current communication technologies, and collect data from those devices and actuate them in a bidirectional communication [104]

Readers are referred to Tables 3 and 4 for real-world implementations of "sTrafficMobility".

Vehicles automation is one step forward toward the fully automated transportation networks as there will be still a need to automate other actors of the transport network such as traffic police agents, highway maintenance, and support teams [98]. The study of the Internet of Vehicles (IoV) has sprung up, where vehicles perform as sensor hubs to capture information by in-vehicle or smartphone sensors, then publish it for consumers [108]. Delay-tolerant data can be offloaded and transmitted through connected vehicle networks without any extra infrastructure or hardware deployment on MEC with vehicles equipped with on-board units (OBUs) connected to the SC facilities using Vehicular Ad Hoc Networks (VANETs) [109]. Private vehicles can perform a variety of tasks like sensing the urban environment from multi-sensor mounted on vehicles or gathering data from the roadside sensors when moving [110]. Dynamic road traffic sensing from travellers in a crowdsourcing way helps manage real-time traffic [63] and the flow of people in cities based on real-time driving and walking dynamics. With vehicle-to-infrastructure (V2I), sensors deployed along the road can monitor the movement of vehicles and if some emergency situation is detected, it can be communicated to the approaching vehicles for actions to be taken in a time-efficient manner [111]. Following the development of IoV and crowdsourcing techniques, Vehicular Social Networks (VSNs) as an emerging paradigm (i.e., the integration of IoV and social networks) are promising to solve the ever-increasing road accidents, traffic congestion, and other such issues that become obstacles to the realisation of smart traffic in cities. VSNs are likely to pave the way for sustainable development by promoting mobility efficiency [108] using conventional V2V and V2I communication frameworks and human factors that impact vehicular connectivity. In the project —scoop@F, carried out by the Ministry of Transport in France, vehicles in city roads will be connected to the smart route and interconnected via Wi-Fi, 4G or 5G technologies to share information about traffic, accident, presence of debris or an animal on the road [12]. Additionally, the use of UAVs for real-time traffic monitoring and management is a promising approach analysed in many studies (Ex: [112]). Readers are referred to Table 6 for more useful UAV applications that can be integrated into SC.

sTrafficMobility should be well-integrated with not only the city sDomains but also all other countrywide domains. For instance, the closest rescue team can be directed to an accident location via an efficient channel (e.g., using helicopters for isolated and rural areas) integrated with sHealthWelfare. Smart work collaboration centres are being established to increase the use of offices effectively, which helps optimise the mobility of the workforce as well with sSocialCommunity integration. The mobility of increasing elderly population is another important issue to be tackled in a smart fashion integrated with sSocialCommunity, and sHealthWelfare. Consumer products and retail industries lose about $40 billion annually, or 3.5% of their sales, due to supply chain inefficiencies [74]. Therefore, the transportation of goods with efficient smart supply chain models integrated into the other sDomains across the nationwide sTransportation, sIndustry, and global smart logistics and retail would benefit all the stakeholders substantially. We would like to note that sometimes the SC applications should encourage the mobility of the people to increase, particularly for social mobility in order to make citizens more social, more productive and more active in contributing to the city social development and peace with social activities (e.g., festivals, open door activities) integrated with sSocialCommunity.

4) SMART ENERGY (SENERGY)

Cities currently consume 75% of the world's resources and energy, which leads to the generation of 80% of greenhouse gases [99]. It is highly urgent to manage energy consumption efficiently and intelligently with effective energy consumption reduction policies and smart technologies where i) the resources are scarce, ii) the populations of cities are increasing rapidly, and iii) the carbon footprint is increasing dramatically. Development of sEnergy cities starts with energy conservation using the concept of architectural designing and building appropriate infrastructure, buildings, parks, playgrounds, other spaces, roads with respect to the environmental factors such as sunlight exposure, shadows, windflow, rainfall, humidity, thermal efficiency, transport networks as can be exemplified in Singapore case.[17] All the smart applications reducing energy consumption and contributing to pollutants (e.g., CO_2, noise reductions, electromagnetic fields) are the subject of sEnergy. Energy sources are also quite diverse, including solar, fossil fuels, gas, electricity, and battery [99]. More importantly, potential renewable energy resources (e.g., solar, thermal energy, wind power) of a city, smart way of storing energy from diverse sources, and conversion of energy from one form to another should be exploited, and accordingly desired supply systems and smart applications should be incorporated into SC to enable more sustainable cities, healthier and more comfortable lives.

Energy-system models have been around for several decades and are experiencing constant evolution to incorporate new technologies and paradigms [113] to manage energy in a smart way. Many cities prioritise sEnergy applications in their SC platforms. Efficient energy management, smart street lighting, smart energy efficient public buildings are the primary areas of sEnergy. sEnergy should be designed to ensure the flows of energy across all the energy-consuming points seamlessly and in an optimised fashion as an integral part of the smart country grid. For this, it should have specialised tools supported by distributed devices to trigger required alarms and actuation in order to both reduce the operational and maintenance costs and improve the quality and reliability of supply systems. In this context, the sEnergy management concept by supporting sGrid is built to monitor

[17] https://www.youtube.com/watch?v=m45SshJqOP4

residents' activity, current, voltage, and maintenance requirements using computers and sensors placed throughout the grid within a city, particularly to optimise the energy usage and to reduce power outages. 40% of a city's electricity costs is street lighting [88]. By deploying smart street lights, SC can reduce the energy consumption by dimming lights depending on the time of day or the location where traffic/pedestrian activities are low [83]. Readers are referred to Table 4 for real-world implementations of ''sEnergy''.

Different sensors distributed throughout a city need to be energy-efficient. More explicitly, data acquisition tools (i.e., UAVs, VANETs) need to reduce their carbon footprint. This can be realised by making these tools more energy-efficient (e.g., energy-efficient WSN), or by incorporating renewable energy sources, where the stored energy can be used at later times [83]. Optimizing sensors' locations, transmitting methods and perhaps scheduling can further lower their power consumption. VLC backscattering, which is starting to show promise in terms of energy efficiency, can also help in lowering power consumption [83]. sEnergy with effective analytical tools should be able to contribute to future short-, medium- and long-term energy requirement plans for sustainable future SCs. This can be achieved by the integration of other sDomains, particularly, nationwide sGrid, sHome, sBuilding, and sTransportation as explained in Section II-D.

5) SMART COMMUNITY AND SOCIAL NETWORKS (SSOCIALCOMMUNITY)

sSocialCommunity mainly aims to make a city more accessible, enjoyable and liveable for both inhabitants and visitors. The main elements of this domain with increased municipal coordination are i) smart public space control and utilisation due to the high density of population in urban areas, ii) smart citizen education and training, iii) smart social networking, iv) smart tourism, v) smart media, and vi) smart community crowdsourcing.

Residents should be trained and encouraged to actively take part in contributing to the realisation of the city mission, vision, and future short and long term plans of SC via smart applications (e.g., smartphones, smart open spaces supported by technology). Smart cities are failing to capitalise on possibilities offered by social media (e.g., Facebook, Twitter and Instagram) where Instagram generates higher levels of user engagement for smart cities [114]. SC integration with widespread social media and city official social media applications can bring many benefits by encouraging user interaction. Furthermore, technological improvements should promote the sustainability of a city by changing the behaviours of citizens. For instance, smart parking meters in Madrid are designed to charge higher rates for less efficient vehicles where fuel efficiency and clean emission is rewarded with a discount (e.g., older and diesel vehicles is charged more) [115]. SiBike - a bicycle prioritisation system mentioned in Table 6 is another good example in this context.

To carry out the tasks in sSocialCommunity successfully, CPSC (Crowd-Powered Smart City: CPSCS stands for sensing where CPSCA stands for actuation) is formally defined as the computing paradigm in SC. With CPSC, the power of crowds including humans, mobile devices, and smart things is utilised to both monitor what is happening in a city, how a city is evolving and take actions to enable better QoL [103]. As the crowd density lived in an urban area is getting higher, in order to improve existing or future infrastructures, public space utilisation involving parks and recreational facilities is crucial for urban developers to understand how efficient these places are being occupied using public space IoT monitoring devices [116]. Effective smart utilities are needed to plan and encourage the use of certain places for both providing equal public spaces between citizens and enhancing community participation and social inclusion. Functional smart tools such as Linguine OS supported by IoT have recently been deployed to control and tailor public spaces according to the needs of the inhabitants and environmental ambiance (e.g., during the daytime or night). Smart social networking is also incorporated into smart community. Recent advances in mobile devices and wireless networks enhance human interaction, which promotes the appearance of ''Internet of People (IoP)''. IoP refers to the digital connectivity of people through the Internet infrastructure forming a network of collective intelligence and stimulating interactive communication among people [34]. Citizens can comment and submit information (e.g., videos, photos) about any real-time event, situation, disaster using crowdsourcing applications and specific social networks via smartphones in order to inform the authorities, media, and other citizens. Citizens, particularly, tourists can be well-informed about the landmarks and social, cultural and economic dynamics of a city with well-prepared applications equipped with sophisticated interactive tools, one example of which is the location-aware city guide services based on open data in Sapporo [21]. Readers are referred to Table 4 for real-world implementations of ''sSocialCommunity''.

6) SMART HEALTH AND WELFARE (SHEALTHWELFARE)

Citizens actively participate in managing their health with sHealthWelfare domain. sHealthWelfare should be planed with the central government as an integral part of the nationwide sHealthcare domain. sHealthWelfare, usually outside of the hospitals, supported by wearable devices equipped with a variety of sensors (e.g., GPS, accelerometer, gyroscope, photodiodes, glucometer, galvanic skin response, temperature) is required to serve the elder people, patients with chronic, contagious or neurodegenerative (e.g., Alzheimer, Parkinson, Huntington) diseases on an anytime-anywhere basis. In this manner, i) smart health education, ii) smart health monitoring, iii) smart medical emergency response and iv) smart elder people and patients with chronic, contagious or neurodegenerative diseases are the main elements of sHealthWelfare. Smart elder people applications are needed to meet the requirements of the increasing elderly population in cities. Patients with certain types of diseases can be monitored and their registered doctors can be informed of proper optimal guidance or therapy within SC. Any health emergency issue such as an accident or emergency health concerns should be responded quickly by dispatching ambulances, doctors or rescue teams. The medical history within nationwide sHealthcare and the current vital signs of the patient should be reached by the authorised medical staff. Routes of ambulances may be shared with the vehicles in the same routes using sSocialCommunity, and sTrafficMobility to help ambulances reach their destinations rapidly. For instance, dispatched ambulances and doctors can be navigated to their locations using intelligent navigational applications integrated with smart traffic lights in sTrafficMobility domain. Readers are referred to Table 4 for real-world implementations of ''sHealthWelfare''.

The majority of mobile devices are expected to be equipped with health sensors which will enable them to test a user's health status, e.g., body temperature, heartbeat, breathing, diet, sleep, and exercise in order to perceive real-time health status [34] and actuate required actions such as advising the user to take any action, informing the user's hospital or doctor. In this context, all citizens should be able to request and take real-time health services under any instant emergency on a pay-as-you-go basis such as heart-attack that requires a quick response.

7) SMART SAFETY AND SECURITY, AND SMART CRIME AND JUSTICE (SSAFETYSECURITY)

The Safe Cities Index which ranks 60 cities across 57 indicators covering digital security, health security, infrastructure security, and personal security places Tokyo at the top and Singapore 2^{nd} [3] and no surprise that SCs find their places in the higher ranks of the declared index. The main elements of this domain are i) smart surveillance (e.g., tracking of a suspecting vehicle, smart plate recognition), ii) smart crime detection and prevention (e.g., human trafficking, smuggling), iii) smart law enforcement/smart crime and justice management, iv) smart emergency (e.g., natural disasters), v) smart public safety (e.g., against terrorism), and vi) smart accident management.

SCs should have the ability to respond quickly to the events related to the safety and security of citizens involving the police, fire department and hospitals to prevent any likely crime or disasters, and most importantly to optimise and organise the entities in SC combined with sTrafficMobility as explained in Section II-C.3. Citizens should be directed to shelters, gathering areas under emergency situations such as floods, earthquakes, hurricanes, and tsunami by smart applications working on smartphones with not-interrupted communication services. sSafetySecurity is supported by AI-driven (e.g., face-driven, specific object driven) surveillance systems. The mobile objects involving vehicles with on-board sensors and residents can be tracked autonomously using intelligent systems equipped with advanced technologies. Additionally, any object, animal, person can be labelled with technological sensors (e.g., RFID, microchips, GPS) and traced against theft or abduction. The people inclined to crime can be monitored using effective smart applications. The collected data based on the crime incidents, crime and safety indexes can be analysed to trigger specific proactive police actions to make a city safer. Citizens can be guided to safer directions regarding events such as social protests/unrest, clashes between groups, and riots. Smart crime detection and prevention along with smart law enforcement can be established based on the intelligent analysis of crowdsourcing data and stream of huge amounts of data acquired from many sensors. All the web of crime organisations from the bottom to the top can be disclosed using effective smart technologies and approaches by analysing city dynamics in coordination with the central government. The monitoring of a city (e.g., detection of traffic violations) with Unmanned Aerial Vehicles (UAVs) utilising the existing public transportation routes including public buses, city trains, shores, and rivers to provide time-sensitive surveillance has been proposed by many studies (Ex: [95]). Readers are referred to Table 4 for real-world implementations of ''sSafetySecurity''.

[18]https://www.mhrs.gov.tr/Vatandas/

[19]https://www.youtube.com/watch?v=rT81J1FjI_U

D. SC INTEGRATION WITH COUNTRYWIDE SMART DOMAINS

The main contrywide domains are sEducation, sGrid, sIndustry, sAgriculture, sHealthcare, sTransportation, sShopping involving smart logistics and retail, sBuilding, and sHome. The objectives in these domains are summarised in Table 7 with their real-world implementations. The connected IoT devices and AMSs in these sDomains not only talk to each other within their domains but also they communicate to other devices in the other sDomains as well, e.g., security, fire or gas alarm using intelligent sensors in sHome or sBuilding may trigger an action for police or fire department within sSafetySecurity in SC [8]. More explicitly, there are no strict boundaries between these sDomains; some of the outputs of the smart devices may input for other smart devices within both their domains and other domains, as illustrated in Fig. 3 in which SC is in the centre to indicate people-focused cyber-physical understanding. One of the recent prominent trends is to integrate all sDomains in a coherent architecture of the cloud platform [120] and a revolutionary networking model called Information Centric Networking (ICN) has recently attracted the attention of the research community working on data dissemination in various sDomains [121]. In this regard, cross-domain data fusion will be an inevitable enabler of SCs in which generated insights turn into input for other sDomains and vice-versa to embrace more useful functions. Furthermore, these insights can help bridge the information gaps, enable more countrywide and global advanced smart implementations and develop smarter value-added services in SC. This can be established by an open data architecture with ''open insight & data pool'' (Fig. 2) in which data acquired by the sensors and generated insights are published within public

TABLE 7. Successful smart nationwide domains needed to be integrated with SC ecosystem.

Application domain	Objectives	Country	Institution
sGrid Gotland	to increase the hosting capacity for wind power, and participation in the electricity market [86]	Sweden	Swedish Energy Agency
sGrid CEHE	to reduce the following: greenhouse gas and pollutant emissions, meter-reading costs, maintenance costs, duration of outages, and theft costs [86]	USA	Department of Energy
sGrid	to create the world's first countrywide smart grid, using ICT to optimise its water and energy systems [23]	Malta	Department of Energy
sGrid	to build a strong smart grid with an ultrahigh-voltage backbone network frame that connects large energy bases and main load centres equipped with 196 million smart meters around the country [13]	China	The State Grid Corporation
sTransportation	to establish connected traffic systems using human factors in traffic [86]	Germany	Ministry of Transportation
sTransportation	to encourages cities to integrate data from multiple sources in order to create accurate models (e.g., shared trunk traffic data, on-demand delivery trucks) in transportation, environment, and energy [34]	USA	Ministry of Transportation
sHealthcare	to monitors for the proper delivery of injections and vaccines nationwide for 2 million patients in 38 states using a new electronic communication system like AmerisourceBergen's to comply with regulations for pharmaceutical pedigrees [74]	USA	Ministry of Health
sHealthcare	to enable all hospitals and medical centres to reach patient's insurance information and basic medical records across the country and help patients take doctor appointment and reach their laboratory results online [18]	Turkey	Ministry of Health
sHealthcare	to dictate the national policies and standards all around the country in order to deliver anytime-anywhere healthcare services and ensure privacy and security concerns	UK	National Health Services
sAgriculture	to increase productivity and efficiency by ensuring food security based on changing circumstances. Ex: farm registering and management [117]; intelligent management of products circulation and management [118]; Intelligent product delivery (RFID, GPS, GIS) [118]	Numerous	Ministry of Agriculture
sEducation	to dictate the national policies and standards all around the country in order to deliver high-quality education by providing equal opportunities	Numerous	Ministry of education
sIndustry	to produce more synergistic products in the light of advanced electronics, computers, intelligent software techniques, Industry 4.0 (4IR), cyber-physical domains, cloud and edge computing [8]	Numerous	Ministry of Economy, Companies
sHome	to provide a comfortable, easier, happier, economical, and functional daily life at homes with diverse smart kits developed by many competing vendors	Numerous	Companies
sBuilding	to turn buildings into living organisms and make big buildings, skyscrapers and big shopping malls more economical, comfortable and functional. Ex: Edge building in Amsterdam (e.g., green; flexible space utilisation: no dedicated desks/rooms) [19]	Numerous	Companies
sShopping	to make the products meet with the customer intelligently. Ex: Amazon Go (just walkout technology): No lines, no registers, no self-checkout machines [119]	Numerous	Companies

domains for researchers, citizens, universities, and companies in order to accelerate the development of further value-added smart services. This, in turn, would contribute to the smartness, functionality, and sustainability of a city. Within this context, Open Sensor Data Platform was developed to specify the standards within the Open Cities Project to serve this purpose [122]. London Open Data with a hub for data about all aspects of the city consisting of over 500 different datasets that the city generates using many sensors all around London encourages researches to explore and build new insights.[20] Readers are referred to Table 1 for real-world implementations of open data hubs. Open data platforms lead to smart countries and smart globe by developing further synergistic implementations such as Thingful[21] by which users can reach a wide variety of real-time data all around the world with efficient visual tools.

We would like to note that in this section, the other sDomains are not the scope of this paper and will not be explained in detail here, rather, their likely interrelations and integration requirements with SC are analysed briefly. Readers are referred to the study [8] for more detailed information about these countrywide sDomains with many examples.

[20]https://data.london.gov.uk/

[21]http://www.thingful.net/

1) INTEGRATION WITH SMART EDUCATION (SEDUCATION)

sEducation with national and international policies should be merged with sSocialCommunity, and sHealthWelfare in SC to help the community improve and prosper, which in turn will contribute to the development of new policies and desired next generations substantially. Citizens can be directed and trained intelligently with respect to those policies. Moreover, current and future workforce development and mobility between cities can be managed effectively with this integration.

2) INTEGRATION WITH SMART GRID (SGRID)

According to published reports, the losses of electrical energy due to inefficient grid systems range from 40 to 70% around the world [74]. sGrid is proposed to solve the challenges of future electricity supply [123]. Developing sGrid is the responsibility of the smart country to increase the efficacy of energy management and delivery (e.g., gas, power supply) throughout cities. sGrid plays a significant role in cost-effective power generation, distribution, transmission, and consumption based on highly volatile demands in cities. sGrid requires the current and future behaviouristic patterns in energy consumption in order to optimise the distribution. More explicitly, load forecasting can be managed effectively in the electricity supply industry where it is crucial to determine future demand for power as far in advance as possible. If accurate estimates can be made for the maximum and minimum load for each hour, day, month, season, and year, utility companies and countries can make significant economies in areas such as setting the operating reserve, maintenance scheduling, and fuel inventory management. It needs inputs from sHome, sBuilding, and the SC domains. Therefore, it relies on millions of smart meters to measure the real-time power consumption in residential areas or buildings and this metering data is aggregated to the control centre to optimise the power distribution in return [97]. In this perspective, sGrid should be well-integrated with the city-driven sEnergy domain to realise its objectives thoroughly.

3) INTEGRATION WITH SMART INDUSTRY (SINDUSTRY)

sIndustry is taking a new form of smarter with advanced automation abilities, increasing international companies, trade partnerships, unions between countries (e.g., EU, Canada-USA), and international joint-ventures. sIndustry should be well-integrated with all sDomains within SC to increase its efficacy, in particular within AoE in order to not only meet the needs of citizens but also tailor their own requirements. For instance, SCs can help the workforce in cities meet proper jobs in industry and most importantly, the workforce can be reskilled based on the specific demands of the industry and the current and future policies. Readers are referred to [8] for more information about the global industry integration with everyday life within the framework of AoE.

4) INTEGRATION WITH SMART AGRICULTURE (SAGRICULTURE)

Reorientation of agriculture is necessary with government policies using intelligent irrigation and livestock management to ensure the countrywide food security based on the changing circumstances (population increase, demand, climate change, irrigation fields, current resources, product diversification requirements, livestock potential, the global trend). In this manner, sAgriculture should be managed in the national domains (e.g., farm registration and farming [117], smart crop monitoring, soil analysis, and insect detection) in order to increase the productivity and efficiency with incentive policies where i) the agricultural areas are out of the cities, ii) different agricultural products can be cultivated in various geographic locations based on the environmental and seasonal conditions, and iii) many products are needed to be imported and exported. Citizens with their immense population are the key factor in determining the agricultural policies. Therefore, sAgriculture should be well-integrated with SC domains such as sHealthWelfare, sEnvironmentMonitor (e.g., weather information, warning under emergency situations such as flood, forest fire, landslide), sTrafficMobility (delivering fresh products intelligently), and sSocialCommunity (e.g., training farmers and consumers) to develop better citizen-centric policies. Additionally, sAgriculture should be integrated with sShopping and sIndustry as well to cope with the changing trends and demands.

5) INTEGRATION WITH SMART HEALTHCARE (SHEALTHCARE)

Healthcare policies should be developed nationwide since any citizen should be able to take the same high-quality national health services on an anytime-anywhere basis with national integrated health records/health units. For this, electronic health records, citizens eligible for the health services (e.g., citizenship query), insurance management integrated with the central government domains should be managed by the central government to deliver countrywide healthcare services by addressing privacy and security concerns. Hospitals are managed with respect to the policies and standards put forward by the ministry of health to provide high-quality health services. An example of this is the National Health Services (NHS) in the UK. sHealthcare should be well-integrated with sHealthWelfare in SC as explained in Section II-C.6. City governments should be aware of the citizens with contagious diseases, chronic diseases, genetic diseases in order to i) provide appropriate services to those citizens locally, ii) protect the overall society from contagious diseases, and iii) direct people about the genetic diseases for healthier societies. In this manner, with a high level of smart coordination and integration, SCs can be supported by the national sHealthcare domain and vice versa, SCs can help central governments develop appropriate sHealthcare policies based on the health information of citizens enabling citizens to access high-quality healthcare services at all times.

6) INTEGRATION WITH SMART TRANSPORTATION (STRANSPORTATION)

sTransportation with smart highways, railways including subways, airways and maritime is designed to manage national and global transportation intelligently. A nationwide transportation using sTransportation is established to connect the towns and cities to each other and sTransportation should be well-integrated with sDomains in SC, particularly, sTrafficMobility, sSafetySecurity, and sHealthWelfare. For instance, sDomains in SC should be fed with the required information by sTransportation if there is an accident on a highway, maritime or airway managed by sTransportation in order to increase the responsiveness. Most importantly, traffic, mobility, and transportation are required to be coordinated to combine the abilities of sTrafficMobility in SC and countrywide sTransportation in order to establish harmonised working systems.

7) INTEGRATION WITH SMART SHOPPING (SSHOPPING)

sShopping involving smart logistics and retail is managed by local, national and global companies to make the products meet the market intelligently. The products should be controlled by the central and city governments to ensure quality and legal health issues. SCs may harness insights that may be acquired from sShopping to develop healthier policies and directions for citizens based on consumption trends. Furthermore, those insights may help develop agricultural policies and may direct the industry to meet the demands of citizens and take necessary steps to improve their products. sShopping should be integrated with sHealthWelfare, sTrafficMobility, sEnergy, and sSocialCommunity in SC in order to function optimally in cities.

8) INTEGRATION WITH SMART BUILDING (SBUILDING)

sBuilding and smart connected buildings are developed to transform buildings (e.g., big buildings, skyscrapers, hospitals, big shopping malls) into living organisms in order to make them more manageable, economical, secure, comfortable and functional (e.g., turning off lights, locking doors, detection/fixing problems with prognosis, diagnosis and self-healing abilities) with optimised building management systems. sBuilding lives in SC and its integration with all the SC domains is necessary to establish an harmonious smart environment. More specifically, the integration of sBuilding with sSafetySecurity, sHealthWelfare, and sEnergy in SC is prime important to make buildings adapt to their smart environment better. sBuilding implementations connected to SC can trigger several actions automatically within SC under any emergency situation such as informing the fire department about a fire. In this sense, many smart buildings were already integrated with the SC domains. Additionally, smart buildings are using many AMSs and IoT devices with many sensors. The number of sensors can be reduced by using the insights/inputs from SC such as local weather and environmental information (e.g., temperature, illumination, humidity) to adjust their functions appropriately [8].

9) INTEGRATION WITH SMART HOME (SHOME)

sHome — home automation with very few industry standards is developed to form a comfortable, easier, happier, economical, and functional daily life with connected IoT devices, particularly using wireless communication technologies. A sequence of events can be triggered to make the life easier and more functional based on the patterns such as while leaving home (e.g., closing curtains, turning off tv, music, heating), when coming home (e.g., opening curtains, heating home, opening your favourite channel), before going sleep (e.g., turn off tv, all lights), before/after waking up (e.g., turning on a favourite channel on tv, preparation of coffee). Energy efficiency is one of the main concerns of sHome. The automated devices at home can be managed using location-independent monitoring and control abilities (e.g., starting a washing machine from the workplace, adjusting the temperature of the home, turning on your lights or opening your curtains when you are on holiday). As in sBuilding, sHome lives in SC and the integration with all the SC domains is urgent. sHome should be integrated with sSafetySecurity (e.g., monitoring of the environment around a house, which may trigger a warning for the homeowner or police), sSocialCommunity (e.g informing, training citizens at their homes), sEnergy (e.g., smart metering), sHealthWelfare (e.g., monitoring of elder people' or patients' health from home, which may trigger an ambulance and/or doctor actuation), and sEnvironmentMonitor (e.g., warning under emergency situations such as flood, earthquake, hurricane, tsunami). The security, fire or gas alarm in sHome may trigger an action for the police, fire department or ambulance in SC [8]. As in sBuilding, AMSs and IoT devices can input much information from SC and all related information that citizens are interested in can be submitted to sHome to inform citizens and direct them accordingly under any emergency situation.

III. INTEGRATION WITH OTHER SCS, AND STATE, COUNTRY AND GLOBAL DOMAINS

The world is changing rapidly with the evolving technologies, getting smaller and becoming more connected to the everyday person. Citizens are not just restricted in a city. The concept of ''smart planet'' proposed by IBM [74] lies in the development of connected SCs and smart countries to cope with the challenges of increasing globalisation. Therefore, expanding the integrated SC domains from a concept of ''city planet'' [124] into a group of integrated SCs, smart state and country domains should be the fundamental objective of developing SCs to both implement optimal solutions in a coordinated and synergistic way and shape the future better with accelerating globalisation. This would generate further economic growth globally with increased QoL. In this sense, the main building block of developing effective smart states, smart countries, and smart planet lies in connecting SCs to each other intelligently with the help of the national and global domains (e.g., GPS, GIS) as illustrated in Fig. 4. Systematic integration and processing of a variety of domains at a time using AIA is highly desirable in order to successfully extract much better insights. For this, open data hubs should be encouraged in SCs and globally on which AIA can process multiple domains for many more useful insights. For instance, in France, more and more cities are releasing open data and the project — OpenSensingCity aims at unifying those datasets with the usage of semantic Web technologies to combine smart cities with a variety of domains [125]. More importantly, international agreed-upon SC development standards, semantics-based ontologies (e.g., Ready4SmartCities, LOV, LOV4IoT, and OSC [125]) should be introduced to ease this process, an example of which is CPaaS.io — an EU-Japan collaboration on data-driven open SC platforms [21].

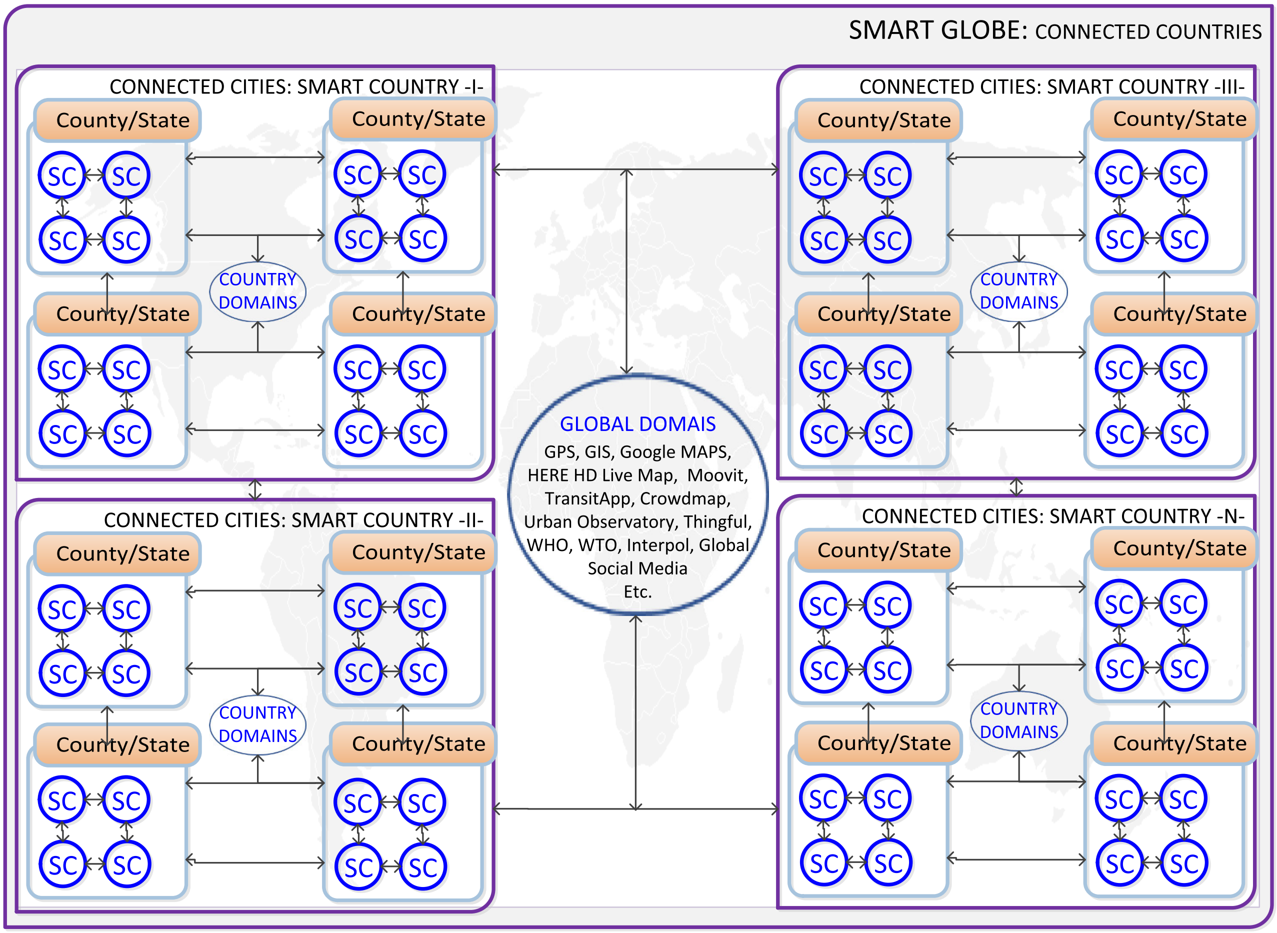

FIGURE 4. Development of smart states, smart countries, and smart planet with the integration of SCs.

IV. PRIVACY AND SECURITY OF CITIZENS IN SC

Privacy protection or even information on privacy policies was found to be scarce in an analysis of 25 SCs with key concerns [126]. Owners of data are concerned with the risks of unauthorized usage of their sensitive data by various entities, including service providers [127] on the cloud platforms, particularly on the private cloud platform. Therefore, they avoid sharing their data with the outside community. How to prevent the sensitive data from unauthorised reading becomes an imperative issue in the development of SC regarding the collection of data from a highly distributed diverse computing environment and immense integration of domains within SC, and with national and global domains. Intelligent surveillance may capture local residents' daily life hints, style, or even privacy, although it was originally designed for monitoring criminal behaviours in the real and cyber worlds [97]. A smart meter installed at each home to collect the near-real-time electricity consumption data to offer better energy services may disclose a user's private information based on electricity consumption profile [123]. The heterogeneity of technologies in SCs makes security and privacy a multi-dimensional problem. Therefore, traditional solutions might not work well to ensure that the privacy and security of citizens is not breached. Attacks on SCs might emerge from the integration of different technologies that are prone to incompatibility issues and in some instances are not built with security in mind [83]. Within this context, in SC, security and privacy concerns arise since the SC applications not only collect a wide range of privacy-sensitive information from people and their social circles but also control city facilities and influence people's lives [97] with autonomous actuation or human intervention. A sophisticated attacker could, for example, take control of various intelligent devices such as lights, cameras, traffic lights, connected cars and many other smart devices in cities [12]. Moreover, these malicious attackers could also launch denial-of-service attacks, disrupting the sensing, transmission, and control to degrade the quality of intelligent services [97]. These concerns hinder the integration of highly cooperative synergistic ecosystems with highly cross-entity data exchange.

Regarding privacy and security issues, the published data should be anonymised to ensure it cannot be traced to a particular resident or household [15]. Sanitisation, e.g., anonymisation/de-identification, and cybersecurity measures to prevent breaches of sensitive information allow the sharing of data for secondary purposes, such as research, establishment of further decision-making tools, extraction of many other meaningful insights that can be useful inputs to other systems. The process of sanitisation is mainly carried out for privacy protection where there is a tradeoff between privacy and utility, which was discussed in [128] and [129]. The threat of predicting sensitive information becomes now a serious issue [129] even after sanitisation process. The sharing of sanitised data should protect individual privacy, but still ensures that the data is of sufficient quality that the analytics is useful and meaningful [130]. Processing of data and sanitisation starts on the edge platform using Advanced Hybrid Cloud-Edge Insight Analytics as illustrated in Fig. 2. However, there is quite an important amount of sensitive data placed in the cloud platform even though most of the sensitive data can be processed and maintained in edge/fog platforms.

The domains, particularly sHome, sBuilding, sHealth, and even sGrid are vulnerable to cyberattacks, particularly with location-independent monitoring and control abilities. What happens if a smartphone operating as an edge platform is hacked by a cyber attacker; cameras that are meant for surveillance may turn into cameras that are violating our privacy [8]. The integration of the SC applications with these domains makes SC more vulnerable to cyberattacks by sharing the data with the outside world and by accepting more authentications and protocols. User's identity and location in transportation, health condition in healthcare, lifestyle inferred from intelligent surveillance, sEnergy, and sHome may be disclosed [97]. Readers are referred to [131] for the recent survey on cybersecurity, data privacy, and policy issues in cyber-physical system deployments in SC.

The techniques and approaches on cybersecurity to address security and privacy concerns are being developed as the cyberattacks are taking place in everyday of citizens in cyber-physical world. Blockchain technology has been recently introduced to mitigate these concerns in SCs. Readers are referred to [132] for the SC blockchain application examples. Edge/fog nodes use protocols that implement authorisation and data integrity, and cloud nodes and every fog node have a certificate, signed by a certificate authority known and trusted by the nodes [41] for trustworthy communication. Additionally, safe communication between the nodes is provided with end-to-end data encryption in order not to compromise the privacy and security of citizens as illustrated in Fig. 2. Moreover, AIA with an ability to work on encrypted data using a number of parameters can be employed as a gate to reach BD, particularly to work on sensitive data to process in order to improve the effectiveness of cybersecurity capabilities without violating the privacy of the individuals. However, encrypting data incurs additional storage and query processing costs — computationally expensive. Additionally, cryptographic schemes and practical systems analysed in a recent study by Moghadam *et al.* [133] enabling the execution of queries over encrypted data (e.g., homomorphic encryption, property-preserving encryption) without decryption using analytics are both non-trivial and costly in terms of computing power and analytic processing difficulties in the fog and cloud platforms. Still, there are serious restrictions in the sharing of data between smart domains regarding privacy and security concerns where data can be reached from anywhere anytime with worldwide distributed computing environments. National and international rules and regulations should be tailored to protect the owners of data. Sharing of data between worldwide smart domains with an effective and efficient infrastructure addressing cyberattack concerns would both inspire data sharing and make the life functional and easier in many aspects within a more integrated environment.

V. CHALLENGES

The essential challenges are summarised as follows:

1) Heterogeneous and highly distributed sets of technologies and concepts: The establishment of seamless harmony between heterogeneous and highly distributed sets of technologies and concepts with their intrinsic complexities involving diverse communication channels is one of the prime challenges in developing SCs.

2) Privacy and security concerns with insufficient standards: Organisations including the International Organisation for Standardization (ISO), the British Standards Institution (BSI), and the Spanish Network of Smart Cities have made progress in the standardisation of SCs, helping to share good experiences as well as assure the role of standards in accelerating SC implementation [134]. However, privacy and security concerns and standards for SCs are not well-addressed by leading organisations, technology companies, and governments as detailed in Section IV. Traditional cybersecurity protection strategies cannot be applied directly to SCs because of the heterogeneity, scalability, and dynamic characteristics of SCs [135]. In this manner, cybersecurity is another prime concern that is urgently needed to be addressed well where the SC applications are increasingly becoming open to public engagement.

3) Lack of data sharing and access control protocols: data sharing and access control protocols are not clear enough. For example, road traffic data can be collected by deployed cameras or travellers' smartphones and GPS in a crowdsourcing way. During global road planning, it is challenging to define the access policy and enable privacy-preserving data sharing among the collaborators [97]. Therefore, the development of sophisticated data sharing policies, approaches, and techniques in SC requires extensive research effort.

4) Lack of AIA and computational overhead: Most of the generated data is wasted without extracting potentially useful information and knowledge because of the lack of established mechanisms and standards that can benefit from the availability of such data [136]. There is a gap in providing efficient and scalable methods that enable near-real-time processing and interpretation of streamed sensory and social media data in the SC environments [5]. The computational overhead poses another impending challenge in terms of efficiency,

especially when massive data are involved in SC [97]. Data generated in different formats, generally not structured exacerbates the situation. Therefore, the highly dynamic nature of SC requires sophisticated AIA that is data-driven, flexible and adaptable to cope with the highly dynamic heterogeneous environment and decentralised intelligence for the management of multi-agent systems harmoniously.

5) Difficulties in crowdsourcing: More volunteers are needed to develop more effective real-time smart applications supported by crowdsourcing, particularly with the engagement of citizens (e.g., sharing the location of their smartphones, vehicles) in order to observe the dynamic environment and provide effective services accordingly and this requires the development of effective incentive mechanisms along with effective privacy and security policies, particularly, with location privacy-preserving techniques. Additionally, the lack of digital skills of citizens poses another significant challenge in engaging with crowdsourcing applications.

VI. LESSONS LEARNED

The lessons learned are summarised as follows:

1) The development of SC should not be left to technology companies. It requires a philosophical multidisciplinary understanding behind technology deployment. Strictly speaking, the development of fully trustworthy SCs requires specialists from a diverse scope of fields involving psychology, legislation, computer, electronics, municipalities, economy, rather than a handful of people in order to ensure that the requirements are met properly and appropriately. The driving force of successful SC development is to engage with all the stakeholders effectively, particularly citizens.

2) The development of SC rises over the city resources. SC should not be developed independently from the city underground and overground resources (e.g., wind, sunshine, thermal water), and the current facilities enabling technological and conceptual social-economic culture.

3) The main objective of SC development is to build systems in an automatic, unsupervised way with no or less human intervention in order to increase QoL. Autonomous decision-making systems require correct and sufficient amount of data in a timely manner, which requires appropriate deployment of sensing and actuating devices over a well-established network infrastructure. More importantly, the algorithms analysing this BD should be selected properly and very well-established in order not to result in disastrous, undesirable decision-making. When there are systematic failures or an algorithm is found to deliver unfavourable outcomes or cause problems, there needs to be a way to "pull the plug", humans must be able to stop the autonomous mode [67] and take over the system easily until the problem is pinpointed and fixed.

4) The lessons learned in Amsterdam [15] are i) technology changes so quickly that officials should not think too much about the technology. The focus should be on the challenges and the solutions needed. The technology will then follow, ii) an open architecture is essential — open software, open infrastructures, and open knowledge, and iii) the understanding of SC changes the way of doing business in various aspects and there are winners and losers in this new business model within organisational change via optimised way of doing things (e.g., office owners may be the losers with the smart office application).

5) Most of the current SC development and enhancement attempts are focusing on urban mobility involving the flow of pedestrians within sTrafficMobility domain as can be noticed in Tables 3 and 4. A huge amount of investment has been underway in sensor-rich mobile devices, particularly in self-driving vehicles to support crowdsourcing applications to be able to observe the instant urban dynamics for near-real-time decision-making.

6) Maintenance costs can be reduced substantially by pinpointing and fixing imminent problems using effective prognosis, diagnosis, and self-healing SC mechanisms equipped with appropriate WSN and IoT deployed properly, and quality uninterrupted public services can be provided.

7) The development of SC is a continuous process and the SC ecosystem flourishes with the lapse of time using plug-and-play abilities supported by well-established integration plans and policies.

8) The programmes and policies carried out by central governments are not sufficient in inspiring, initiating and directing SC projects. It is envisioned that by the middle of the century, city and city-region management will have become one of the primary delivery vehicles for national policies [1].

VII. DISCUSSION

The SC use cases that receive the most funding in 2019 include fixed visual surveillance, advanced public transit, smart outdoor lighting, intelligent traffic management, and connected back-office and these five use cases will represent 34% of worldwide spending [14]. The current well-advanced technologies may address most of the challenges in SC development and support the sustainability of a city substantially. Additionally, there are well-established international (e.g., C40, Eurocities, ICLEI, SC World Expo, and UN-Habitat [1]) and national (e.g., The UK's Centre for Cities, UK's Cities Standards Institute, Future Cities Catapult, Centre for Digital Built Britain, Scottish Cities Alliance, and The Smart Cities APPG [1]) organisations to direct the development of SCs. However, our experimental evaluation of the current SC initiatives demonstrates that still there is a long way to go for these cities to be really smart within a robust integrated infrastructure although each SC initiative has its own merits with the particular smart components used. In this perspective, despite increasing momentum in SC development initiatives, the Smart Cities APPG in the UK declared that "the government needs a new strategy on SCs" because there are no effective national policies to direct the city governors to follow [1].

We analysed the literature and current SC projects in detail to find a starting point that shows the milestones to build SCs in our district. We have come to the conclusion that there is no ideal unique SC to take an example and there is no ideal ready to use smart city development framework to follow. While smart city assessment schemes have been around for about a decade and despite the proliferation of smart city assessment schemes, there has been limited research on their structure and typology [137]. Current SC initiatives have various particular successful sub-domains, but, lack in embracing most of the smart domains mentioned in this paper. Additionally, the city and nationwide smart domains within existing SC examples are not well-integrated and not ideally built both to serve the sustainability of a city and to enable positive behavioural changes with effective citizen engagement. Regarding the literature, most of the publications focus on particular sections of the SC development (e.g., smart traffic, smart energy) and lack in giving a holistic comprehensive development roadmap with proper integration requirements supported by sophisticated knowledge. Readers are referred to [131] for one of the latest SC development reviews.

Within this context, to contribute to the existing literature related to smart cities, this paper focuses on the philosophical aspects of building sustainable SCs and a SC development framework — TCitySmartF that embraces the ideal features of recent successful SC initiatives, future SC development plans, many other particular SC development solutions and customisable approaches tailored by city dynamics and human factors is developed. More explicitly, TCitySmartF outlines a SC roadmap from the technological, social, economic and environmental point of view, particularly by both putting residents and urban dynamics at the forefront of the development with participatory planning and interaction for the robust community- and citizen-tailored services. Engaging with the public sector, local businesses and community is the prime driver behind the evolution and development of SC platforms to precisely meet the needs of residents and cities. A system that enables citizens to let city authorities know which services they feel are unsatisfactory can provide a sense of engagement, ownership, and civic responsibility, and give city authorities direct feedback on city services [25]. Therefore, the future SC platforms are aiming to involve more citizens in the development and enhancement of these platforms. Increasing citizen engagement with the SC domains via crowdsourcing help observe the city's instant dynamics and enhance the SC domains. However, the lack of digital skills of residents poses a significant challenge in engaging with citizens thoroughly. For instance, 11 million people in the UK do not have the basic digital skills needed to thrive in today's world [1]. Of individuals in the US with an income lower than US$30,000 per year, approximately 40% don't own a smartphone [138]. Those people are usually more vulnerable sections with low well-being levels. Therefore, their needs are urgent to be incorporated into SCs and more importantly, they would be a valuable asset for crowdsourcing applications if educated sufficiently. The SC movement has been growing worldwide, but it will take another couple of decades for SCs to realise their game-changing potential [1].

VIII. CONCLUSIONS AND FUTURE RESEARCH IDEAS

The demands of city services equipped with better infrastructure and smart technologies are increasing at an alarming rate as the urban population continues to rise with many challenges to cope with. This paper analyses the past, present, and future of SC development initiatives from a philosophical point of view supported by sophisticated knowledge 1) to reveal the best practices, 2) to unveil novel resource and citizen-centric, and user-driven opportunities, and finally 3) to outline how to harness smart technologies in developing SCs in order to make smarter and more sustainable cities by mitigating the challenges of rapid urbanisation. As a result, a framework — TCitySmartF is established by combining the physical city and digital world using a comprehensive dynamic city automation roadmap with its four essential dimensions as illustrated in Fig. 1. TCitySmartF aims to establish SC that not only functions harmoniously with its well-integrated city components but also functions smoothly with the components in its surrounding ecosystem — national and global environment. More explicitly, TCitySmartF points out the guidelines and milestones in next-generation SC development initiatives, particularly the development of more sustainable SCs flourishing based on the particular city dynamics, and resources. The smart domains in SC both adapt and change the dynamics of a city substantially, which in turn changes the way of living and behaviours of citizens leading to the realisation of the mission, vision, and sustainability of a city in a more quality and democratic city ecosystem.

The city councils of Lancashire and Preston in the UK and the University of Central Lancashire are collaborating to transform the cities in the Lancashire district into smarter cities based on the central government initiative and funding. In this manner, this paper is developed to shed light on how to transform a city into a smarter city. The proposed framework involving the best practices along with the useful future ideas mentioned throughout this paper is going to be incorporated into these real-world SC development projects. In this perspective, this paper is expected to direct other similar SC development projects as well. The main smart domains mentioned in this paper will be analysed further and new research papers with the gained hands-on experiences will be published for each particular smart domain as our real-world SC projects progress.

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