IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 24, 2021, accepted October 12, 2021, date of publication October 15, 2021, date of current version October 27, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3120843

Digital Twins From Smart Manufacturing to Smart Cities: A Survey

GEORGIOS MYLONAS[1], ATHANASIOS KALOGERAS[1], (Senior Member, IEEE), GEORGIOS KALOGERAS[1], CHRISTOS ANAGNOSTOPOULOS[1], CHRISTOS ALEXAKOS[1], (Member, IEEE), AND LUIS MUÑOZ[2], (Senior Member, IEEE)
[1]Industrial Systems Institute, Athena Research and Innovation Center, 265 04 Patras, Greece
[2]Department of Communications Engineering, University of Cantabria, 39005 Santander, Spain

Corresponding author: Georgios Mylonas (mylonasg@athenarc.gr)

This work was supported in part by the Project "I3T—Innovative Application of Industrial Internet of Things (IIoT) in Smart Environments" (MIS 5002434) implemented under the "Action for the Strategic Development on the Research and Technological Sector," funded by the Operational Programme "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014–2020), and in part by Greece and the European Union (European Regional Development Fund).

ABSTRACT Digital twins are quickly becoming a popular tool in several domains, taking advantage of recent advancements in the Internet of Things, Machine Learning and Big Data, while being used by both the industry sector and the research community. In this paper, we review the current research landscape as regards digital twins in the field of smart cities, while also attempting to draw parallels with the application of digital twins in Industry 4.0. Although digital twins have received considerable attention in the Industrial Internet of Things domain, their utilization in smart cities has not been as popular thus far. We discuss here the open challenges in the field and argue that digital twins in smart cities should be treated differently and be considered as cyber-physical "systems of systems", due to the vastly different system size, complexity and requirements, when compared to other recent applications of digital twins. We also argue that researchers should utilize established tools and methods of the smart city community, such as co-creation, to better handle the specificities of this domain in practice.

INDEX TERMS Digital twin, smart cities, industry 4.0, society 5.0, IoT, smart manufacturing, cyber-physical systems, open challenges.

I. INTRODUCTION

Ever since big technological advancements in microcontrollers, MEMS sensors and actuators, and novel networking technologies started to make their way into the mainstream during the late 1990s and early 2000s, the research community began to discuss and work at a rapid pace towards the interconnection between the physical and the digital domain. This was done initially with the work of the research community on wireless sensor networks, and subsequently with the Internet of Things (IoT), which has already become ubiquitous and a part of our daily lives in just a few years. Cyber-physical systems (CPS) have also facilitated this transition, especially when discussing in the context of smart manufacturing and Industry 4.0.

Based on the advancements in such fields, and combined with the cataclysmic shift towards the integration ofc Machine Learning (ML), Deep Learning (DL) and Big Data from all things digital, another significant concept has risen to broaden the scope of this digital/physical domain interconnection and expand the field of the applications utilizing it, that of the Digital Twin (DT). With CPS evolving as a cornerstone concept exploiting enabling technologies of Internet of Things and leading to an integration of Information Technology and Operation Technology [1], the Digital Twin has transformed into a strategic technology, offering virtual representation of the physical world, simulating the behavior of physical things throughout their lifecycle, while maintaining permanent connection between the physical and virtual parts. In this context, further to being an engineering practice, Digital Twins could be viewed as cyber-physical systems on their own, dealing with data exchange and the interconnection of physical and digital parts at a plethora of domains [2].

Furthermore, in order to understand the reasons behind these trends, we should keep in mind the disruptive

The associate editor coordinating the review of this manuscript and approving it for publication was Kai Li.

potential of digital twins as regards simulation of large, complex systems. Until recently, in such simulation scenarios we had to resort to trade-offs between model complexity, execution time and accuracy, where software simulators utilized limited datasets, which could be real-world traces or synthetically generated, to produce results in an offline/asynchronous manner about the systems we wished to study. However, with the advancements that facilitated the progress in digital twins [3] (ML, Big Data and IoT) and the creation of many actual instances of such systems, now the simulator and the model can essentially be a digital twin, continuously evolving as it is fed with new data from the real world. Especially in the field of smart manufacturing, where in scenarios like predictive maintenance digital twins have begun to show their potential, this new range of available options has led to the proliferation of the use of digital twins in production. General Electric in a recent report [4] stated that its digital twins have helped in saving $1.05 billion US dollars per year by avoiding customer, production, and mechanical losses. According to other estimates [5], the digital twin market is projected to grow from $3.1 billion US dollars in 2020 to 48.2 in 2026. It is thus obvious that digital twins have already started having a significant, tangible impact.

Apart from the undeniable effect of DT technologies in system simulation, other benefits have emerged through the rising number of DT applications. Simulation is mainly used during the first stages of conceptualization and system design. However, the growing need for monitoring and control of systems and products throughout their life-cycle requires the creation of data-driven models that enable the real-time acquisition and analysis of data for complex systems. Digital Twins can provide an in-depth view of large and complex physical systems in real time, something that would otherwise be almost impossible to achieve [6]. The volume of real time data available can raise system efficiency through providing users with deeper insights on system operation, while the possibility to handle a complex physical system through digital means opens new avenues in terms of safety. As mentioned above, life-cycle management is becoming extremely important not only for individual products but also for entire systems in operation. Tracking of changes in system implementation is therefore critical for troubleshooting and finding optimal solutions. Digital Twins offer the chance to keep versioning information on an evolving variable system, providing system designers with data on implemented changes, as well as the ability to backtrack to a previous implementation in order to test new ideas during the redesign stages.

Getting back to the origins of DTs, we have witnessed a progression from their first steps in NASA, using them to simulate systems in space, to holistic representations of more complex processes and systems. Historically, the "Digital Twin" term was mentioned for the first time in its current setting in 2003 in the context of product lifecycle management (PLM) [7]. From there on, digital twins quickly jumped to smart manufacturing, and are currently mostly associated with the Industry 4.0 concept, while we are also witnessing other domains, like smart cities, beginning to utilize DTs. In this sense, DTs seem to be ever-evolving, while their definition has also followed suit, with the first definitions being more suitable to the industrial and smart manufacturing sector, and gradually using more flexible ways to define what a digital twin is and what it can do.

Having the above in mind, in terms of research questions (RQ) that we wish to answer with this work, the following are discussed here:

RQ1 What are the key differences between digital twins in smart manufacturing and smart cities?

RQ2 How is the DT concept being applied into the smart city domain and which are its key application areas thus far?

RQ3 Which are currently the open challenges as regards the application of DTs in the Smart City domain?

Regarding the methodology used to survey ongoing work for digital twins for this paper, we have resorted to sources such as Google Scholar, ResearchGate, Semantic Scholar, in order to gather a pool of work that includes recent papers and links to research projects related to digital twins, along with search results from tools like CORDIS [8]. We have resulted with a total of more than 130 recent papers on the field, references to projects, prototypes, tools and products, which we believe provide a fairly representative view of the current situation in this specific research field.

What has become immediately apparent after surveying the current state-of-the-art research in this domain is that the issue of the DT definition is perplexed by the fact that several communities are involved in their implementation in different application domains, each one seeing DTs from their own perspective. This evolving nature of DTs has led to a diversification of the DT definition, in some cases based not only on a technological standpoint. This is further accentuated when comparing between DTs in smart manufacturing and smart cities: in contrast to industrial DTs, technology is not enough on its own when discussing DTs in conjunction with smart cities, since they entail the participation of several communities as well. We are also seeing DTs being gradually introduced to a wealth of different key application areas, such as urban planning, smart mobility, and environmental monitoring. Likewise, since DTs are being applied as a novel instrument in these areas in cities, there are still a number of open challenges; on the one hand, there are technology-related challenges, regarding standardization and the implementation of what are in reality "systems of systems", and on the other hand, there are community-related ones, centered around the participation of the various parties involved in smart cities and the use of established tools and methodologies in the area, like for instance co-creation.

Regarding the structure of this work, we continue with a brief mention of the history of the development of the DT concept and its definition, along with a discussion regarding its application in smart manufacturing, which has been the most popular application domain of digital twins so far. We follow with a discussion on the smart city domain, the differences, and the specific requirements on utilizing DTs in this domain. A discussion on the existing work surveying the digital twin domain follows, along with a presentation of related reference models and standardization activities. We continue with a presentation of DT-related works on smart cities, across a multitude of application domains. A series of recent and current projects and prototypes are discussed, together with existing DT tools and products. We follow with a discussion on open challenges and then conclude the paper in the final section.

II. A BRIEF HISTORY OF DIGITAL TWINS AND THEIR APPLICATION IN SMART MANUFACTURING

Although the concept of the DT is not particularly new, it has only been in recent years that we witnessed a huge surge of interest towards it, mainly in the form of its applications in smart manufacturing and Industry 4.0. Historically, the first actual DT is associated with NASA's Apollo 13 mission in 1970, three decades before the appearance of the term in literature [9]. The notion of a physical system some 200,000 miles in space and multiple simulators used to train both astronauts and ground control staff on different failure scenarios, presented a digital twin associated with a physical asset, receiving feedback from it and being connected, the simulators being adaptable and reconfigurable to new conditions, dealing with different aspects of the mission, and being responsive to critical damage of the physical asset.

As mentioned previously, one of the earliest appearances of the term "digital twin" was in 2003 [7] in the context of product life management (PLM). The term resurfaced more broadly in literature in 2010 in NASA's "Draft Roadmap on Modeling, Simulation, Information Technology and Processing", and its final release in 2012 [10]. First works on DTs were mostly associated with aircrafts, and the aviation industry, although some initial works in manufacturing date to 2013 [11]. One of the first works presenting a product avatar as a digital counterpart of a physical product not being strictly associated with aviation appeared in 2015 [12], thus opening the way for the wider use of the term in other domains. From there on, smart manufacturing starts to dominate the digital twin domain, with the respective influence on the DT term definition, opening up the terms used in earlier descriptions and adding terms used in the smart manufacturing domain. The following definitions, highlighted in [13], give some insights regarding the evolution of the "digital twin" term in recent years:

- "A digital twin is a virtual representation of a physical object or system – but it is much more than a high-tech lookalike. Digital twins use data, machine learning, and the Internet of Things (IoT) to help companies optimize, innovate, and deliver new services" [14].
- "A digital twin is a virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning and reasoning" [15].
- "A digital twin is a virtual representation of a physical entity or system. The digital twin is much more than a picture, blueprint or schematic: It is a dynamic, simulated view of a physical product that is continuously updated throughout the design, build and operation lifecycle. The digital twin and its corresponding physical object exist in parallel, evolving together as the physical product progresses and matures" [16].
- "In the context of Digital Built Britain a digital twin is a realistic digital representation of assets, processes or systems in the built or natural environment" [17].

Just by reading these definitions, one can see that current DTs focus on dynamicity, learning and evolution, instead of being mere digital shadows of static objects in the real world. There is also an emphasis on *systems* instead of just *objects or entities*, while the last option, coming from community close to smart cities and urban planning, gives a definition in the context of this application domain that also includes assets, processes and systems. In the near future, we expect that we will see additional DT definitions that adhere to the requirements of new application domains, but also enabled by future technological breakthroughs. Regarding such future DT instances, [18] discusses cognitive digital twins and provides several predictions. In any case, the DT definition is still evolving and appears to be guided by the prevalent trends and uses in specific application domains.

Back to the present and understanding how DTs in smart manufacturing have shaped the current DT landscape, the DT concept tries to answer specific technical questions with reference to the manufacturing industry in the context of Industry 4.0 transformation [19]. Modularity, autonomy and ubiquitous connectivity open new perspectives in manufacturing, allowing new production opportunities, comprising distributed manufacturing, automatic planning and execution of orders, dynamic reaction to new orders or disturbances for automatic rescheduling of production, improved decision support. In order to achieve all these, there is a need for data collection, and information seamlessly made available throughout the lifecycle of the production process.

The combination of the IoT, CPS and DTs serve this purpose. CPS are integrations of computation with physical processes. Physical processes are monitored and controlled by embedded computers and networks, with physical processes affecting computations and vice versa [20], [21]. While embedded systems focus mainly on computation, CPS focus equally on computation and communication between computing and real world entities [22]. CPS comprise sensors and actuators for accessing the physical environment. They benefit from and act as an enabler for the fast growth of the IoT. The IoT represents a network of physical objects or things made possible to interact through the internet. Its novel paradigm, building on top of embedded computing, sensor networks and pervasive systems, enables the variety of things around us to interact and cooperate towards achievement of common goals [23]. CPS may be also viewed as IoT–connected things that combined with data analytics and AI can enable smart systems in different application domains including smart cities [24]. The notion of CPS at the cross section of the physical and the digital world discerns them from conventional information systems. CPS via interacting physical and digital components with sensing, control and networking functions influence the real world through physical processes [25]. By providing digital descriptions of physical objects, CPS extend real world objects to the digital world, directly associating with digital counterparts of the physical world or DTs [26]. DTs represent large collections of digital artefacts, with meta-information and semantics, offering simulation capabilities and enabling model-based systems engineering. They address their physical world counterparts throughout their lifecycle offering valuable services to a multitude of application domains.

There is a certain ambivalence in the understanding of the DT concept and its dimensions. In [27] it is proposed that the DT comprises five dimensions: physical part, virtual part, connection, data and service. In [28] a review of 50 research articles, 8 patents and 6 leading company best practices is performed with reference to Digital Twin application in manufacturing. The paper identifies as theoretical foundations of Digital Twins: modeling, simulation, verification, validation and accreditation, data fusion, interaction and collaboration, and service. Industrial main applications of Digital Twins include their utilization in product design, in the production process, and in Prognostics and Health Management (PHM). Under-explored application areas include dispatching optimization and operational control. Cyber-physical fusion is ruled out as the most pressing issue in the development of Digital Twins.

In [29], a review of 41 recent papers is performed. The DT is viewed as a living model of a system continuously updated with data from its operating physical twin. Digital Twin utilization in industrial operations, especially production phases and predictive maintenance, is quite significant, yet after-sales services utilization remains limited. Challenges associated with the implementation of Digital Twins in industry include lack of methodology and standardization, data fusion, complexity, model high fidelity, servitization, security issues, and high cost.

A recent comprehensive survey [30] reviews 240 relevant publications as regards the concept, technologies and applications of DTs in industrial settings. The authors argue that the DT concept is currently general and ambiguous, and that it should evolve to something more concrete. DT applications in industry are discussed, together with a set of observations and recommendations, categorized according to lifecycle phase (design, manufacturing, service and retire phase). They also argue for cooperation to define a more systematic architecture of DT research.

As systems in industry become smarter, they actually represent systems of systems, with their smart components being systems on their own. Simulation at system level is needed to be possible to efficiently deal with such systems of systems. Detailed digital modeling is deemed necessary for this task. Complexity is also growing. To deal with such challenges [31] proposes "Experimentable Digital Twins" (EDT) for simulation-based engineering processes. Thus, diverse application scenarios, called "simulation-based X", are induced allowing simulation-based engineering, optimization, reasoning, verification and validation, control and HMI (human-machine interfaces).

TABLE 1. Abbreviations used in the text.

Abbreviation	Stands for
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modeling
CDBB	Centre for Digital Built Britain
CPS	Cyber Physical System
DL	Deep Learning
DT(s)	Digital Twin(s)
DTC	Digital Twin Consortium
GIS	Geographic Information System
HMI	Human-Machine Interface
IDTA	International Digital Twin Association
IIoT	Industrial Internet of things
IoT	Internet of Things
JTC	Joint Technical Committee
MDS	Mobility Data Specification
MEMS	Microelectromechanical Systems
ML	Machine Learning
N/A	Not available
PHM	Prognostics and Health Management
PLM	Product Lifecycle Management
RQ	Research Question
SDG	Sustainable Development Goals
VR	Virtual Reality

DTs can help resolve security issues in industrial control systems and CPS in an efficient manner. As DTs are actually evolving digital models that mimic their physical counterparts, they may be used for detecting deviations between expected and real system behavior by incorporating threat detection and prevention measures, thus managing security issues [32]. Utilization of DTs for testing purposes in the industry can help test CPS resilience against diverse attacks without risking real operating physical systems [33].

III. THE SMART CITY - A SYSTEM OF SYSTEMS

In this section, we proceed to examine the general setting as regards the gradual introduction and utilization of DTs in the smart city landscape. Cities, in general, can be thought of as living systems, even as "organisms", due to their largely dynamic nature, sheer complexity and size. This goes well also with the definition of DTs as living, evolving models, entities and systems of the physical world. Currently, around 55% of the global population lives in urban areas [34], and this figure is expected to grow to 68% by 2050. Such trends, along with the same technological advancements of the past decades, that have helped to kickstart DTs, have facilitated the implementation of smart city projects around the world.

When discussing the basic aims of a DT in a smart city context, we should also have in mind the fundamental goals of smart cities themselves. Although the definition of the smart city has, in a similar fashion to the DT definition, been evolving through the years, there are some broad categories of goals that many smart cities aim for, like facilitating better governance through better-informed decisions, improving citizens' well being, cutting down operational costs, providing disaster management/mitigation, and supporting development and business uptake. In light of these aspects, we are now witnessing DTs in smart cities turning into reality [35].

A starting point in this process is essentially the replacement of conventional simulations in cities with DTs. In our opinion, given the advances in smart city deployments and DTs, use-case scenarios like projecting in real time the effect of changes in traffic flows inside urban areas on the mobility of citizens, or calculating the effect of a rainstorm on the level of a river's water and creating potential risk management scenarios, are beginning to sound as a plausible DT application in smart cities. Such scenarios reveal the potential of the combination of smart cities and DTs to provide cities with the means to make well-informed decisions in specific domains. In some ways, previous smart city research projects, like SmartSantander [36], were precursors to this city-scale DT vision, by aiming to create new development ecosystems around smart city data marketplaces.

However, this potential has not been fully revealed or utilized thus far, and we have only witnessed modest DT implementations within smart cities. Up until now, the most popular interpretation, by far, of DTs in a smart city context has been the geospatial mapping of urban areas to 3D models combined with associated data from existing city datasets, together with real-time data from smart city deployments (to a variable degree). This precedence time-wise was potentially due to the interest shown in early stages by the architect and urban planning communities to apply DTs in cities, or familiarity with Building Information Modeling (BIM) processes of these communities, which present similarities with DTs. However, we believe that the potential applications of DTs to smart cities transcend this context; as presented in the following sections in this work, DTs are already being applied towards achieving the general smart city goals mentioned in the previous paragraph.

We also have to keep in mind that we are talking about systems of systems in the case of smart cities; even with small islands of IoT deployments covering mobility, environmental monitoring, waste management, etc., it is needed to also take into account the other existing information systems of a city, the big data produced by city-owned sensors and the ones owned by citizens, the increasingly connected vehicles, among other, just to give a few characteristic examples. All these can be thought of as a large distributed system, which differs considerable from the cases e.g., of having a DT for preventive maintenance of machines inside a classical industrial environment, where apart from the considerably smaller system complexity, there is also a much more stable environment, except from times for the reconfiguration of a production line, or events of similar nature.

Moreover, and even as importantly, apart from the technological aspects of introducing DTs to smart cities, there are the aspects tied to the multiple communities and stakeholders in smart cities, which in turn influence some technological aspects as well. For instance, there are the city authorities and related stakeholders, like politicians, that would most likely initiate the process for implementing a city DT and the multiple city services that could benefit from it. There are also the citizens that could act as both end-users of the DT and as data providers, as well as the multiple businesses that could utilize the outputs of the DT. On top of that, there is the issue of data ownership; data could be produced by a publicly-owned infrastructure, but in some cases data could be provided by private companies or citizens. These are issues that are rarely, if at all, encountered in the Industry 4.0 setting, with much more deterministic processes in terms of data production. There is also the issue of public user interfaces, since citizens should be involved in the process of using smart city DTs and reaping the benefits from their use; in industrial environments, there is no such requirement. Finally, there are also the co-creation processes utilized in smart cities by all participating communities and stakeholders, which we believe should be a part of a successful DT design and implementation.

Another aspect which is seldom discussed and that could receive some boost by the use of DTs is the interaction and collaboration between different smart cities. Currently, there are very limited or non-existent intra-relations between smart cities e.g., for developing collaborative models for disaster management, pollution monitoring or circular economy flows. One could imagine in such a setting use cases where the DTs of one smart city alerting the civil protection authorities of a nearby city and the respective DT utilized to model potential disaster management scenarios as early as possible. In light of recent extreme weather events due to climate change, such as extreme floods, this is a quite timely scenario. We could also argue that the concept of smart city DTs as systems of systems could even include collections of such DTs, creating even larger systems.

Moving back to the current breed of DTs in cities, a recent work [37] focuses specifically on city-scale DTs and is close to our own perspective for DTs. The authors argue that thus far DTs have been studied and applied much more in a smart manufacturing setting and, due to this fact, current research is "largely confined to a technology-centric view with a main purpose of demonstrating technical functionality". This point of view limits their applicability in smart cities, since they are much more complex and heterogeneous systems, which in practice will require to take into account the urban and socio-political context of cities to produce workable solutions and useful results. The authors present their perspective using the example of the work for Cambridge and the UK in general, with initiatives such as the CDBB [38] (Centre for Digital Built Britain) that have produced the Gemini principles [17]. The authors also give a definition of DTs in cities stating that "City-Scale Digital Twins are digital representations, or ''virtual replicas'' of cities that can be used as simulation and management environments to develop scenarios in response to policy problems''. Although not encompassing all aspects of such systems, we believe that this definition represents quite well the scope and aims of current DTs in smart cities.

IV. EXISTING SURVEYS OF THE DIGITAL TWINS DOMAIN AND STANDARDIZATION ACTIVITIES

As mentioned in the previous sections, there has been a wealth of activity regarding DTs in recent years, with a number of survey papers documenting, and reviewing the progress in the field. The multitude of application domains of DTs is also reflected in such papers, where in many cases the field is surveyed from the viewpoint of the research community or the industry, or in other cases using the optics of a specific community, such as urban planners or the Internet of Things. However, until now there has been a distinct lack of focus on the synergies between DTs and smart cities, partly owing to the fact that several of these surveys were compiled by authors outside the IT community. In terms of methodology, the entirety of these surveys has followed standard practices such as using search engines and reliable repositories such as the Web of Science and Google Scholar to compile lists of papers containing keywords close to the DT domain, and then compiling the final lists of works to be presented in such surveys. We should note that the number of such articles grew considerably after 2019, showing the potential in the field.

A survey paper from the viewpoint of using DTs in the industrial Internet of Things (IIoT) and in the context of Industry 4.0 is [39]. One of the central aims of this paper was to discuss the various definitions of DTs and its progression, along with related misconceptions. An overview of DT applications is presented, emphasizing smart cities, manufacturing and healthcare, paired with a survey on state of the art on these domains. From the list of works presented, it is evident that there is a multitude of works focusing on smart manufacturing rather than smart cities, with the number of the latter being a fraction of the former. A set of open challenges for each of these 3 areas is provided, along with more general ones. The authors conclude that there is a need for standardized data models, to evaluate and compare heterogeneous DTs in several areas, integrate latest advancements in AI and IoT, develop secure solutions, and work more on data exchange. [40] similarly emphasizes the use of DTs in Industry 4.0 and manufacturing, giving further weight to the critical part of big data in this domain, and argues that several open challenges in DTs are directly related to big data.

Another recent survey [41] focuses on the various definitions and characteristics of DTs, following a chronological approach and presenting the various ''incarnations'' of the DT concept, from early NASA examples to more recent ones. The authors argue that the DT definition has evolved through the years to include additional dimensions and characteristics. It also presents a set of application domains (manufacturing, aviation and healthcare), with the respective design implications for DTs. An interesting aspect of such implications presented is the need for the utilization of a sociotechnical and collaborative design approach for DTs, which is especially relevant to the aspects discussed here, i.e., for applying them to smart cities. Among the open challenges mentioned, ethics, security and privacy are once more highlighted, together with the cost of development of a DT instance, which currently is prohibitive for certain scenarios like healthcare. The importance of working on user interfaces for creating and operating a DT is also highlighted.

Reference [6] has a rather different focus compared to the aforementioned surveys, choosing instead to present the methodologies and techniques for constructing DTs from a modelling point of view. Apart from healthcare and manufacturing, it categorizes DTs to ones related to meteorology, education, cities and energy, and discusses the enabling technologies in such domains. The authors argue at the end of the paper that although industry will probably be the sector pushing strongest for DTs in the coming years, effort should be placed in democratizing access to DTs, in order for the benefits of such technologies to reach wider parts of the society.

Regarding DTs in cities, the Gemini principles [17] (mentioned in the previous section) have began to influence recent work on DTs. A recent white paper [42] by the IET regarding DTs in the built environment follows the logic laid out in the Gemini principles, but also highlights the milestones towards producing actual DTs that are cost-effective and produce value for cities and citizens. It proposes an industry-agnostic maturity spectrum model for DTs, in order to conceptualize the different elements needed in DTs to deliver different levels of value for cities and the society overall.

An interesting take on surveying the status as regards the use of DT in the IoT context is presented in [43]. The authors argue that the intertwining between the use of DT in manufacturing, advancements in VR and AR, multi-agent systems and virtualization will allow to create a consolidated definition of DT. They also briefly present aspects of smart-city focused scenarios for DTs, arguing for the use of open standards, as well as considering self-organization aspects in DTs, since the scale of urban DTs will be prohibitive for human intervention and configuration. The authors also argue that although DTs appear to be useful to several domains, they still need their merits beyond the basic scenarios, and that there are open issues like privacy and security. As regards enabling technologies for DTs, [3] provides a lengthy discussion on current technologies used to implement DTs in various domains. The authors argue that due to the multiplicity in protocols, formats, etc., the current breed of DT-related tools is not as integrated as it could be and that new tools still need to be developed to accommodate DT-specific workflows.

Reference [44] focuses on DT applications targeting maintenance, which has been described in several survey papers as one of the most popular use cases for DTs thus far. It discusses the different types of maintenance for which DTs can be used (reactive, preventive, condition-based, predictive and prescriptive maintenance), and presents the different application fields for such types of maintenance that are combined with a DT. The authors argue that manufacturing is by far the most popular application field for DTs and that, in this context, maintenance is one of the most popular subjects in recent years. They conclude that there are two major challenges still open in this area, with the first being the lack of data availability and the second being the need for definition of maintenance procedures.

Regarding the use of DT in the oil and gas industry, [45] provides a recent survey of the area. In similar fashion to many other papers referenced in this section, it first discusses aspects tied to the definition of DTs. The authors describe the 3 key application areas for DTs in this sector, i.e., asset integrity monitoring, project planning, and life cycle management. They also argue that cyber security, lack of standardization, and uncertainty in scope and focus are the most important open challenges. They conclude that the use of DTs in this domain is still relatively at an early stage, as indicated by the big increase in the number of research works in this domain from 2017 and on, a remark shared by other papers surveying other application domains of DT.

As regards the potential of city-scale DTs, [46] discusses in length such aspects, although this is done more from an urban planning point of view, leaving the discussion relating to other smart city areas in the background. However, the authors stress the importance of having the stakeholders and the end-users of such DTs in the loop when designing and implementing such systems, due to their characteristics. In this sense, they also stress the importance of visualization in such DTs, and how it still is an open challenge for the full utilization of the urban DT potential. The authors also provide an overall research agenda and open challenges for the area.

A recent report by the JRC [13] presents a more expanded collection of recent research on DTs, including a discussion on the evolution of the definition of the term. The presented work serves to prove that as the field of application of DTs expands, so does its definition. The report is also one of the few works giving special weight to applications in smart cities and relevant standardization efforts, such as those led by ISO's JTC 1 information technology committee [47] and the related advisory groups. A number of smart city DT efforts are also presented, providing further evidence of the growing interest in this specific domain.

Regarding standardization in the DT area, as mentioned above, ISO/IEC JTC 1 Information technology [47] Advisory Group 11 (AG11) has recently began its activities on DTs. In this context, the Joint Advisory Group (JAG) Group on Emerging Technology and Innovation (JETI [48]) that was set up in 2016 between the IEC and ISO Joint Technical Committee (JTC 1) is also looking into aspects related to DTs. Thus far, it appears that currently there are very few such initiatives taking place, in contrast to the conclusion reached by many of the works mentioned in this section, which specifically call out for action on defining common open standards to help bring additional momentum and direction, especially in the case of urban DTs. A small number of standards that are directly related to DTs have began to appear, such as [49], which focuses on integration of DT in manufacturing.

Another standardization-related effort from the side of the industry is the Digital Twin Consortium [50], an effort led by the Object Management Group. Its founders include Ansys, Bentley, GE Digital, Microsoft, among others, i.e., companies with DT products currently available in the market, as mentioned also in Section VI-B of this work. Overall, it aims to drive best practices and requirements for standards, in order to provide a reply to several of the open challenges referenced in Section VII, such as the lack of standardization and interoperability, as well as creating cross-industry DT reference architectures and definitions. The Industrial Digital Twin Association [51] is another related effort, focusing exclusively on industrial aspects of DTs, with a number of high-profile manufacturers participating.

Regarding the overall definition and taxonomy of DTs, [52] reviewed 233 papers and proposed a taxonomy based on 7 dimensions: i) Data Link, ii) Purpose, iii) Conceptual Elements, iv) Model Accuracy, v) Interface, vi) Synchronization, and vii) Data Input. The authors also remark on the rapid increase in the number of research papers directly referencing DTs in the last few years, and how currently there is a very active debate regarding the definition of the DT term, with their work a step towards helping define the DT landscape better. Overall, we agree with their assessment about the definition of DT and one could argue that as DTs are being applied to new application domains, this situation is expected to continue for a few more years.

Regarding the utilization of AI, ML and Big Data in the implementation of DT, [53] provides a thorough survey of the current landscape. As is the case with most surveys in the area, it also touches upon the issue of the DT definition, tying it to the history of the field and its uses in real-world applications thus far. It provides a detailed discussion on matters related to these technologies and DT, while also surveying the set of tools utilized for such aspects in DT, which in many cases are not DT-specific. Smart cities are referenced as one of the fields where there are market opportunities for DTs, together with optimization, predictive analytics, process monitoring and healthcare, thus suggesting that this domain is still to be developed in comparison with e.g., DT in smart manufacturing.

As a recap of this section, out of the aforementioned recent works, some of them deal explicitly with aspects of DTs in smart cities, and that is done to a variable degree. In contrast, smart manufacturing is mentioned in all of them, and this could be translated as follows: DTs in smart manufacturing have established themselves as a concrete tool, however, the respective situation as regards smart cities is still quite fluid. In addition, the lack of a widely-agreed definition and taxonomy for DTs at this point, the relative lack of standardization activities thus far, as well as the efforts in the area led by different communities adds to the overall sense of

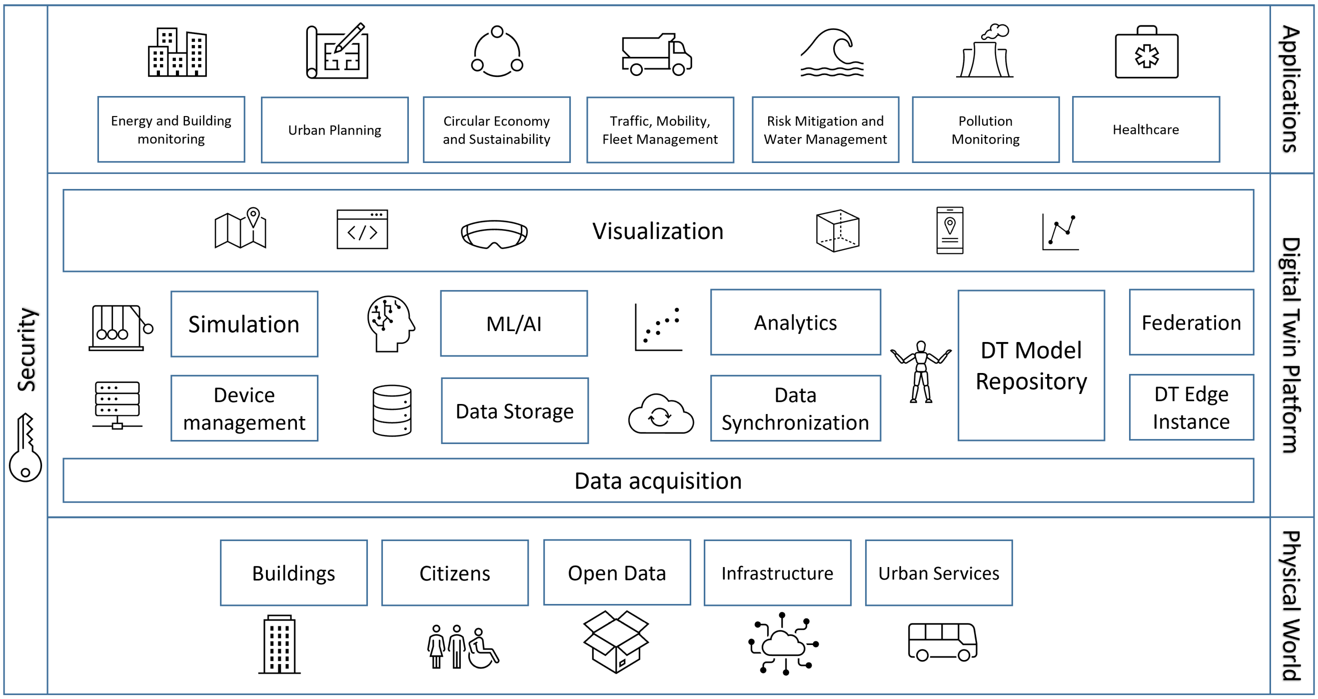


FIGURE 1. A high-level overview of a city-scale DT, its main components, real-world data sources and significant application domains tackled thus far. Data acquisition mechanisms forward data from the real-world to the main components of a DT platform, where e.g., ML/AI-based approaches can be utilized to process such data and then perform simulations based on the models available in the DT model repository. Through the visualization components available (e.g., Web portals, VR, 3D models and maps) and depending on the specific application domain, results can be delivered to end-users, or other systems, while security traverses the whole stack.

the smart city DT field being at a crossroads, trying to find the way forward. Moreover, there is a general agreement in most of these survey papers that there has been a noticeable increase in research output related to DTs from 2017 and on, which to a certain degree could signal that the field has not had the time to mature enough yet.

V. DIGITAL TWINS IN THE SMART CITY DOMAIN

In this section, we proceed with a survey of recent and current work utilizing DTs in the smart city domain, presenting representative work on a smart city application sub-domain basis. In Fig. 1, we show a high-level architecture for a city-scale DT, including the key technologies, main components, main data sources, as well as the application domains presented in this section.

A. ENERGY, COMFORT AND STRUCTURAL HEALTH IN BUILDINGS

Energy is among the most important resources for the operation of a city; from large metropolitan areas to small cities, everything from buildings, transport, infrastructure and services requires enormous amounts of energy. It is no wonder that the energy sector was perhaps the first application area related to smart cities to be involved in the Digital Twin concept. The interest in building and grid energy efficiency and the availability of smart energy metering devices have certainly pushed towards novel DT approaches in the energy sector.

Reference [54] suggests an approach towards smart city DTs involving the collaboration of technologies like Artificial Intelligence and Machine Learning, based on semantic modelling and data driven rule-based reasoning, to aid in the collection and processing of data, identification of events, and automated decision-making. In this context each city domain, from infrastructure to services and environment, is modeled using ontology classes and properties, while for each domain the specific rules that relate to its operation are defined. The combination of these creates the data model which is used as input for the Machine Learning techniques which in turn can provide clustering and classification of city objects, as well as associations between them, leading to automated knowledge extraction through data mining. The authors also present the implementation of this specific architecture in a use case for the city of Chicago. Using energy bench-marking data, the resulting DT model can effectively categorize buildings based on usage, extract parameters that identify buildings within specific areas, and divide the city into energy usage related blocks. This knowledge provides city stakeholders with enhanced levels of situational awareness and decision-making support for the management of urban infrastructure.

Reference [55] analyzes the concept of urban scale energy models and their increasing contribution in assessing the energy performance of buildings in city scale simulations. A city building data-set is used as the basis for the development of a 3D representation of the city structure.

Afterwards, the researchers applied three different models on the acquired data to simulate the energy consumption and assess the energy efficiency of buildings, a machine learning hourly consumption model, a GIS-based engineering model to predict space heating consumption and a software simulation model to estimate energy demand and use. The models were implemented in the case study of Fribourg in Switzerland and the results indicate that urban-scale energy models can be used to identify smart energy solutions for sustainable cities and policies, and to support energy and environmental goals.

Reference [56] focuses on a unified open-source optimization framework as a solution to the challenge of multi-vector smart energy systems in the smart city domain. It proposes the integration of an intermediate software control and coordination layer, called the Sustainable Energy Management System, between the Smart City Digital Twin and the actual assets of the city. This layer implements Machine Learning algorithms and Model Predictive Control strategies to provide smart focused solutions to energy efficiency related problems that are known to exist in city scale environments, by delivering recommendations to lower-level actuators. The system communicates with the DT, receiving predictions based on the DT energy simulation tools and updating the DT with real time and control data. This proposed architecture provides a high degree of scalability, as each subsystem can be considered and integrated independently with an additional coordination layer used to impose higher district-level constraints and limitations.

In [57], the authors discuss the importance of DT enabled energy management platforms in facilitating both energy efficiency prioritization and near-real-time decision making. A visual representation of the city DT that transforms energy related data and metrics into useful information such as temporally segmented building energy benchmarks can aid city energy managers in adopting the best energy efficiency strategy for large scale building areas.

Reference [58] provides a review of DT-based approaches regarding intelligent recommendation systems for energy services, as well as demand side management. The authors discuss the popularity of the intelligent recommendation systems in the energy sector after 2013, and the growing use of the DT concept after 2018, after having a slow start in previous years. A set of policy recommendations for the adoption of DT in the energy sector is also provided.

Authors in [59] point out the usefulness of a DT city model in raising citizen awareness on energy related matters. By showcasing energy related data, such as energy consumption, renewable energy generation and storage, as well as real time data from smart metering devices and weather data from weather sensing equipment installed in the Trent Basin in Nottingham, UK, users were able to visualize the energy usage of their city. This Citizen Information Center proved that DT implementations can help raise awareness of citizens and provide useful feedback to communities and decision makers on matters of energy efficiency and environmental protection.

In [60], a DT application is created through the merging of BIM and IoT technologies, targeted at city energy efficiency and healthy sustainability in terms of promoting social well-being, environment protection and economic boost of the area. User comfort is directly related to indoor environmental quality (IEQ). Several models combine multiple IEQ parameters, comprising acoustic comfort (AC), indoor air quality (IAQ), visual comfort (VC), thermal comfort (TC), and represent the relation between occupant satisfaction and objective measurements. Environmental data is collected from various sensors and used to calculate a set of predefined indices that measure the energy efficiency of the buildings. These indices are used as triggers to provide actuation instructions for the building to regulate its energy consumption and internal comfort conditions. Camera lenses capture the facial expressions of occupants and facial recognition algorithms relate them to their emotional state. All this processed data is visualized in a 3D environment of the buildings, which integrates energy measurements, comfort related indices and emotion detection into a real time comfort visualization environment.

DT applications in the building structural health section focus mostly on critical infrastructures, with a particular interest in bridges. Authors in [61] suggest a DT approach for accurately monitoring the stress and strain conditions of a functional bridge in real time, while visualizing information from IoT sensors in a BIM 3D environment. The DT fuses together two approaches for bridge performance monitoring, the physics based numerical modeling approach and the data driven statistical modeling one. The resulting data centric engineering approach integrates data and BIM to improve the whole-life management of the bridge structures.

Another application for bridge structural health monitoring aims to automate and enhance risk inspection procedures [62]. 3D scanning and visualization in a DT environment can help engineers make better informed decisions without the danger of subjectivity of manual inspections. Simulation of human imposed risks like heavy traffic is another benefit of DT both in the construction and in the operation monitoring phase of a bridge life-cycle.

In [63], geospatial point clouds are used for the generation of a 3D BIM of a bridge. Integration of data from the bridge structure, including real-time IoT sensor data in a unified data structure allow for simulation of bridge operation and maintenance by also utilizing machine and deep learning techniques to reduce the uncertainty in manual configuration of critical variables for the structural health of the bridge.

It is clear that the DT paradigm is gaining momentum in the energy efficiency sector, which is inadvertently connected to the Smart City concept. The large volume of available real-time data on building energy performance through the spread of IoT technologies is providing the necessary basis for energy efficiency calculations. BIM technologies are used as a means to visually represent the energy performance of buildings, offering energy managers and officials more user friendly platforms on which to base their decision making, while enhancing citizen participation and raising awareness on energy related issues. The use of Artificial Intelligence and Machine Learning technologies are being used extensively to process big data and extract useful results that can aid in prioritizing energy related retrofits and interventions. Another strength of DT models that stands out when talking about energy efficiency, but also when considering the structural health monitoring of infrastructure is the ability to accurately simulate different scenarios and present city officials and planners with solid knowledge of the achievable results or dangers related with the operation of the city.

B. URBAN PLANNING

The increasing number of inhabitants in metropolitan areas and the limited space and resources for city expansion makes urban planning and simulation of proposed measures and constructions vital for the sustainability of implementations. DT applications can aid in this context, while also increasing citizen participation in policy making.

Reference [64] presents a method for creating spatial 3D models that are used for city scale DTs. The method involves using near real time data from sensing equipment forming Light Detection And Ranging (LiDAR) point clouds to facilitate the unsupervised development of a 3D representation of the city. A method for clustering objects through exploiting their symmetric properties is implemented and tested in a car park in the city of Dublin. The use case validation shows good results compared to previous work and proposes a solution to the problem of unknown taxonomies of city objects when trying to model them in 3D environments such as in DT applications.

Reference [65] highlights the importance of integrating different technologies like cyberGIS, BIM, AI, Machine and Deep Learning, laser scanning, surveying using unmanned aerial vehicles and IoT stationary and handheld devices into a unified data management system to create a dynamic DT of a city. Dynamically created point clouds can be communicated to stakeholders and experts via cloud-based platforms to aid decision making processes. The paper focuses on the usage of such a system on construction planning and on measuring the impact of new structures on city organization and development, while pointing at several difficulties including spatial big data analysis requiring high performance computing environments. The paper also provides a review of proposed simulation algorithms and models related to GIS and DT applications.

Reference [66] presents the usage of a city-scale DT to promote citizen interaction with authorities and to facilitate their involvement in the city planning procedures. The DT model is broken down into 6 discrete layers. The basic layer is the terrain, incorporating elevation information and data from soil maps. Buildings and infrastructure layers contain the Building Information Modelling and 3D street maps. The mobility layer is used to simulate urban mobility of citizens and goods and connects to the Unity3D model through the Traffic Control Interface. The final two layers are the Smart City layer, which represents the IoT devices of the city and the Virtual Layer that presents the DT. These two layers exchange data and information with each other, allowing the system to be used in simulating different scenarios such as skyline and green space building and presenting outcomes to citizens and authorities for valuable feedback and re-planning.

Urban planning procedures represent challenging tasks for city officials with regards to optimal decision making, selecting sets of measures that produce the least amount of disturbance and negative impact on other aspects and citizen involvement and acceptance. The DT model offers integration opportunities for a large amount of technologies that generate the required amount of data to support this complex decision making process. Representation of city environments is performed dynamically through point-cloud technologies. This allows for an actual visual presentation of city structures that are planned to undergo changes long before anything is actually implemented. Scenario simulation is also of utmost importance to present both officials and citizens with feedback on positive and negative outcomes of the planned interventions.

C. CIRCULAR ECONOMY AND SUSTAINABILITY

There are several works associated to Circular Economy [67] and Circular Cities. A number of them refers to the emerging Circular City paradigm and its technology enablers that actually represent also parts of a city DT although not specifically mentioned as such. In [68], reference is made to RESOLVE [69] conceptualization for circular economy. The author identifies shortcomings for its application in the context of Circular Cities. Urban systems present high complexity involving multiple actors. Consumption has to be addressed further to production in order to facilitate circularity at city level. Land and infrastructure further to materials, energy and water are identified as significant resources for cities. Adaptation is essential at city level in order to become more circular. Localization is important as scale of activities is at city level. The proposed conceptualization comprises three circular actions: loop, adapt and regeneration of the urban ecosystem, and four support actions: localise, substitution, share and optimise. The UN Sustainable Development Goals (SDGs) [70] provide sustainable world targets. SDGs 11-13 address specifically the circular economy and can be used in the context of circular cities as targets for sustainable cities, consumption and production, and climate action.

In [71], the authors present a conceptualization of core aspects of circular cities. Application of circular principles in urban planning and support of ICT solutions are presented as technical enablers for circular economy in cities, while technological lock-in is regarded as a challenge. In this context, circular cities can be facilitated by the introduction of standardized ICT. Internet of Things can for instance enable fine-grained and continuous asset tracking. In [72] the authors address IoT introduction and deal with security and privacy issues of IoT devices through the use of Blockchain technology along with Edge Computing so as to address IoT devices resource availability. Hierarchical Edge Computing is discussed as a suitable architecture in the smart city context.

A few recent works deal with DTs in the context of the Circular Economy and the Circular City. A literature review of 46 papers with reference to remanufacturing (''the rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired and new parts'', [73]) in construction and the application of DTs is provided in [74]. Lack of data and difficulty in exchanging information in the remanufacturing chain are identified as the main challenges in construction waste remanufacturing. The application of DTs in the construction industry covers mostly design and maintenance, while being rare in the demolition phase. The concept of using DTs for remanufacturing related to the Circular Economy is addressed by a rather limited number of works, focusing mainly on manufacturing waste and component remanufacturing. The authors identify data integration, information communication, and integration of decision support models as indispensable components for DT applications in the construction sector, addressing the Circular Economy perspective.

In [75], a laboratory application case is presented, related to the support of the Circular Economy concept by Industry 4.0-based technologies. A virtual test on waste from an electrical and electronic equipment disassembly plant configuration made use of a set of enabling technologies comprising CPS, IoT and DTs. This allowed both design stage prognostic assessment and real-time synchronization between the digital and physical world and related optimizations, with CPS being the cornerstone of the overall modelling effort. Energy-related KPIs are introduced to evaluate the system's energy performance. The work presented provides a digitalization of the Circular Economy paradigm, addressing resource efficiency and lifecycle management, as well as process effectiveness in an Industry 4.0 modelling context.

In [76], the authors analyze the contribution of DTs in sustainable production. The main research questions stated are how to derive an appropriate definition of sustainable production from the sustainability concept, and which are the basic DT requirements. DTs are viewed as an enabling technology for improved execution of sustainable production relevant strategies. A review of the state of the art research related to DTs and sustainability concepts (life cycle, recyclability, environment, etc.) reveals that there is a limited number of relevant works employing a bottom-up approach focusing on DT-supported methods and patterns of sustainable production and related technical challenges. The proposed top-down perspective presents a normative systems thinking interpretation of production, requiring for its industrial application the resolution of existing methodological sustainability science hurdles, data exchange between production units, and a collective impact assessment holistic control of production. The authors derive 10 major requirements for DTs, out of which data interoperability and access rights, environmental data compilation, and environmental impact modeling are currently handled by existing works. Future DT research for addressing sustainability involves chemical composition and physical design transparency issues serving environmental compliance and disassembly, linking to material and substance composition models, and sustainability relevant sub-models addressing the need for secondary use of substances in a lifecycle perspective, as well as interlinked ecosystem sub-models.

In [77], the authors deal with DTs as tools for sustainability assessment in buildings. Their Sustainable Digital Twin (SDT) framework presents dynamic real time monitoring of sustainability indicators that can be utilized in building lifecycle, e.g., during building maintenance. The paper moves from static rating approaches to DTs out of BIM utilizing IoT building infrastructure. A pilot deployment of the SDT is presented in an academic building of the University of Brescia, Italy.

Although waste management is one of the major concerns in smart cities, especially in large metropolitan areas, at the time being it appears that there is a lack of research linking DT applications with it. A comprehensive review of the current state-of-the-art in waste management in smart cities is provided in [78]. It also presents key elements that should be in smart cities' strategies for them to become zero-waste sustainable cities. Just from the number of the papers reviewed (more than 220), it is evident that this area is currently quite active, due also to the interest in sustainability and circularity. However, although up until now the utilization of DT in waste management appears to be almost non-existent, we anticipate that in the near future we will begin to see samples of this approach in practice, at least in prototype form.

Summing up, there is currently a great deal of activity joining the Circular Economy, Sustainability, CPS and IoT. We are beginning to gradually see a small number of works introducing DTs to this application domain, and more specifically in cases where remanufacturing and sustainable production is the goal, or in sustainability assessment in buildings. However, the application of DTs for circular economy and sustainability in a smart city context currently appears to be quite limited, or it is done indirectly via other application domains. We believe that this is bound to change in the coming years, and scenarios like waste management seem as good candidates for the potential utilization of DTs.

D. TRAFFIC, MOBILITY AND FLEET MANAGEMENT

One could argue that several of the first DTs in the urban space were implemented as parts of mapping services realization efforts (Google Maps, HERE, etc.), since essentially the production of detailed maps of cities entails the extraction of features from the real world and their transformation to digital ones, while also keeping them periodically updated. In this still evolving space, there are currently competing visions; essentially, the DT can provide a foundation for developing services either through a private companies' point of view, or from the point of view of cities' authorities. From the point of view of the private sector, the currently prevailing business model involves building a closed-source DT of the physical world, in order to utilize it for providing mobility-focused features. The rise of autonomous driving has pushed this direction further, either through the availability of such features in available passenger cars, or through the efforts of companies aiming to produce fleets of self-driving taxis, like Waymo and Uber. Having a DT of the urban space can help in providing more advanced autonomous driving features, better mobility and passenger itinerary scheduling, etc. Essentially, in the case of simulating autonomous driving features in simulation settings that mirror the ones in the real world, DTs are a direct response to this real-world business use-case in the automotive industry.

From the point of view of city authorities, such a DT could be more open, or even open-source, in order to facilitate the implementation of applications, such as dynamic congestion pricing in urban areas, or delivering more timely and accurate data about road events, such as accidents. In this space, the Open Mobility Foundation [79] (OMF) has recently published the Mobility Data Specification [80] (MDS), as a means to standardize the interoperability between different actors in the mobility sector, so that both cities and companies can utilize such kind of data in a commonly-agreed manner. For instance, private companies that operate e-scooter fleets could report related data using MDS. As an example of traffic-focused simulation studies based on such real mobility data, [81] presents a DT-based simulation study in Berlin, with results supporting that using various transportation modes in Berlin can effectively reduce travel time in the city.

In this context, the current breed of electric vehicles appears to be leading the way regarding the use of Advanced Driver Assistance Systems (ADAS) and other IoT-based technologies. It is apparent that the importance of system software for vehicles has been growing exponentially, to the degree that it seems that car manufacturers should evolve into software houses as well. Reference [82] provides an analytic review of the state-of-the-art as regards the use of DT technologies in electrified vehicles, and discusses the workflow for developing a DT for such vehicles. The authors also discuss the benefits of utilizing DT technologies in this space, especially in terms of vehicle health management, battery management and intelligent charging. Regarding current open challenges and setbacks to using DT technologies the authors single out the lack of standardization and concerns to security and privacy, since the inclusion of a large number of networked components in such environments carries inherent risks of this type. Another recent report on the state-of-the-art regarding electric vehicles [83] also emphasizes the use of DTs to provide better predictions on the operation of the vehicle, as well as for predictive maintenance. Reference [84] discusses a DT framework proposal over a vehicle-to-cloud based ADAS, arguing that such systems can benefit transportation systems in terms of mobility and sustainability, while at the same time having acceptable communication overhead. Reference [85] uses a DT-based approach to study the issue of EV charging and discharging at a large scale, arguing that such an approach can be effective in this domain. A proposal for utilizing a low-cost prototyping platform for implementing a city street-level DT is presented in [86], as a more practical approach to construct a basic street-level DT in urban areas.

As regards DTs for managing commercial EV fleets, the organized adoption of electrified public transportation vehicles in China has facilitated the development of software solutions for monitoring the status of networked vehicles out in the roads, essentially creating an EV fleet DT. Reference [87] showcases a current implementation in this domain in Shenzen, China, for operating a fleet of 38.000 electric vehicles (buses and taxis), allowing for almost real-time monitoring of their status. Moving on to types of mobility other than passenger vehicles on roads, there are ongoing efforts concerning the use of DT technologies in last mile logistics, such as in the case of the LEAD H2020 project [88]. The project aims to create DTs of urban logistics networks in 6 European cities (Madrid, The Hague, Lyon, Budapest, Oslo, Porto), targeting tools for evaluating the impact of using alternative logistics strategies in such environments, and overall aiding stakeholders to take better-informed decisions in logistics scenarios. The evaluation of such scenarios is expected to be implemented using living labs methodologies [89], which are among the established tools used by the smart city community for several years. There is also the use case of using DTs for maritime traffic and tracking of smart containers in ports, like in the case of the port of Rotterdam [90], which is the biggest port in Europe and sixth biggest in the world in terms of cargo throughput.

On another front, proposals and prototypes for utilizing DTs in the mobility, traffic and fleet management sector have raised several flags among privacy experts as regards potential misuse of such data. The possibility of either private entities or public authorities having access to data that can be deanonymized in this application domain is one of the factors that currently seems to drive the public discussion around DTs in mobility and traffic management, and for good reason. It is obvious that data produced from smart vehicles and smart city infrastructure can present several potential privacy risks to the passengers of the vehicles, or even to passersby in certain scenarios. In this context, [91] discusses a DT-based prototype with mechanisms for detecting privacy anomalies and minimizing privacy risks in a "smart" car.

Overall, DT technologies seem to be well-timed to utilize the advances in autonomous vehicles and appear to go together well with the currently ongoing wave of electrification of mobility. There is an evident interest by both private and public entities to utilize such approaches in order to bring forward the vision for autonomous driving and implement better traffic management, and, at the moment, it seems that this is one strong use-case scenario for utilizing DTs.

Since the field is still quite new, some of the challenges we see in most DT domains are here still quite evident: standardization, scale, security and privacy concerns are all issues that appear to be open. However, it also seems likely that advances in smart cities, electrification of vehicles and ''softwarization'' of the car industry will help to accelerate things in these aspects.

E. RISK MITIGATION AND WATER MANAGEMENT

During the last 20 years, we have witnessed the effects of climate change in the form of a growing number of extreme weather events [92], [93] and their associated costs worldwide. A large part of such events are related to water, in the form of either draughts or floods, while the current projections for sea level rise in the coming decades are cause of great concern and alarm. At the same time, we are currently witnessing the effects of the COVID-19 pandemic, which has exposed to a certain degree the deficiencies in disaster risk management in many parts of the world. The word ''resilience'' has entered the public discussion surrounding cities and communities, indicating a realization of the extent of the effects that such events potentially have, as well as the importance of having risk mitigation mechanisms in place. To a great extent, these events have triggered a renewed interest in utilizing the technologies developed in the past few years to develop smart city solutions for crisis management, utilizing all the information streams available to provide a more accurate picture of the real-world parameters affecting the outcome of such events.

An attempt at describing a generic framework for a city-scale disaster management system is presented in [94]. The authors argue that such a system can be based on multi-sensory data streams, data integration and analytics, game-theoretic decision-making, and dynamic network analysis, presenting also a discussion on the current open challenges for each of these components, as well as the role of AI in this domain. Reference [95] discusses in a similar context the use of participatory sensing to enhance existing DT data, such as 3D models, through crowdsourced visual data. The authors conducted small-scale case studies in Houston, USA, to showcase the potential of the proposed approach.

As regards the management of health crisis like the COVID-19 pandemic, [96] proposes a DT-based approach utilizing federated learning, i.e., with a shared produced model but with data kept locally for privacy reasons, for planning COVID-19 response management. Their simulation results over a real-world dataset showed promising potential for such an approach, which essentially federates multiple DTs to produce a more general view for crisis management.

With respect to managing events related to water, [97] argues that hydrological DTs can be valuable tools towards safer urban areas, by focusing on floods and interconnecting with other DTs, such as traffic or urban planning-focused ones, enabling the various city stakeholders to communicate more efficiently with each other. In similar fashion, a DT prototype [98] focusing on the water network system was developed in Newcastle, UK, that can potentially track both malfunctions in the network, as well as the effects of a heavy rainfall that can have an effect in the level of water in certain areas/buildings, allowing for better response planning to such situations. Reference [99] discusses the implementation of a DT model for the water distribution network in Valencia, Spain.

Overall, although it is evident that risk mitigation could potentially be an important application domain for city-scale DTs, at the moment it appears that the number of implemented DT-based prototypes and solutions is quite limited. One could also note that the scale of the implementation is quite small in almost all respective deployments, which could indicate hidden costs and complexities in implementing and operating related DTs in practice.

F. POLLUTION MONITORING

Pollution monitoring is crucial in every city as decreasing pollution is a key factor for citizen health and well-being. We are starting to see DT applications deployed to address this area, with a clear focus mainly on air quality and secondly on noise pollution in urban environments.

In [37], a city-scale Digital Twin prototype is presented as a means to aid policy making to tackle four important urban area issues: congestion, air pollution, growth management, and the limited capacity of the local energy infrastructure in the Cambridge city region. The same system is presented in [100] as a prototype that quantifies some of the inter-dependencies among transport, air quality, housing and energy infrastructure in the area. The model is constructed following three inter-connected tasks. Firstly, past trends regarding the problems are identified. Following this first exploratory phase, scenarios are developed and executed, while in the final phase the model is connected with existing city models on transport, pollution and energy to create a unified knowledge base used to promote coordinated policy making. Prototype building is based on the propositions of the ''Gemini Principles'' on creating city-scale DTs.

Reference [101] proposes the development of GIS-based city monitoring/city management applications. This effort requires the fusion of different technologies like GIS, BIM and IoT. IoT nodes provide real-time information on several useful data including air and noise pollution indices. This data is fed into the data layer of the model, which consists of BIM objects. A GIS system is used as the integration platform, as well as for visualization of the acquired information. This approach of a DT representation of a city using different technologies offers independence from the specific underlying type of technologies used, enhanced monitoring of urban and building conditions and crowdsourced monitoring of occurring events.

Reference [102] describes a city-scale DT prototype for the city of Herrenberg in Germany. The model integrates BIM and visualization technologies with several computational methods that use sensor acquire data to simulate scenarios useful for city monitoring and decision making. Computational fluid dynamics applications were used for air flow simulations, while data from installed sensors were used as input in air pollution simulations to adhere to the main problem for the city. Researchers point to the challenges when embedding the DT in the smart city paradigm, namely promoting the understanding of the potential and limitations of implementing digital technologies in cities and using these digital technologies as solution-oriented approaches. In terms of pollution, the importance of air quality for citizen health is underlined and the problem of emission mobility and the resulting subjectivity to a high level of spatial and temporal variability is highlighted. The DT prototype relies on air quality readings acquired via crowdsourcing and air pollution simulations based on OpenFOAM [103].

Reference [104] delves into the process and challenges when creating a DT with geographical focus for the city of Vienna. The paper hints at the usefulness of such a model on other uses, by discussing the effect of the level of detail of city 3D representation on simulations that calculate the dispersion of noise pollution inside a city structure.

Another city-wide DT is used in the city of Zurich as described in [105]. The basis of the model is the spatial 3D model of the city, which is updated and enriched with real time data in order to facilitate its use in several applications like noise and air pollution modelling. A work in progress is presented, as the 3D spatial data is continuously expanded, covering several applications like thermal monitoring of the city and promoting the active digital participation of citizens in urban planning procedures through an attractive visualization of the acquired data. The authors point out the importance of using open spatial data in promoting dissemination and creating new applications.

Overall, the majority of the pollution and environmental monitoring DT applications in the Smart City domain focus on noise and air pollution. The collection of air pollution data from sensors coupled with the model's ability to apply computational fluid dynamics algorithms offer the ability to actually visualize air pollution levels through the city. Noise propagation through city structures can also be simulated using a 3D GIS layer. Providing advanced public DT-based visualization options of these common city issues could also aid in raising citizen awareness on environmental issues, as well as help to adopt a more eco-friendly approach on the usage of polluting resources and operations.

G. HEALTHCARE IN SMART CITIES USING DTs

The utilization of sensors and IoT within healthcare has really taken off during the past few years and it is currently one of the most active fields in terms of both research and commercial applications. One could argue and the health-related sensors and related services in our smartwatches and smartphones are now a commodity. Moreover, apart from being used on a personal health level, their application in COVID-19 pandemic management has showcased their potential uses on a community level, e.g., Google [106] and Apple [107] have made publicly available statistics as regards changes in mobility patterns of people using these companies' mapping services and mobile device location history data.

This duality of targeting health-related applications at both a personal and a community/organizational level is gradually being transferred to the DT as well. Sensors from both personal devices, like smartwatches, and smart city sensing infrastructure can be employed to enable such applications. In this context, DTs e.g., of human organs can help to model/simulate the effect of treatments, while smart cities can use DTs to respond to potential and actual dangerous situations as regards health, e.g., air pollution affecting the health of citizen inside a certain urban area.

As an overview, [108] provides a discussion on the ways smart city and other technologies can be utilized to make healthcare ''smarter''. More specifically, the authors argue that both smart city infrastructure and mobile sensors, together with machine learning to enable more effective and lower-cost healthcare services for smart city residents. A number of use cases for ICT-based healthcare at a personal and community level are presented, while also examining the relationship between aspects such as city planning and walkability. As regards open challenges, the authors focus on privacy and security, accessibility and usability, together interconnection with smart city services.

Focusing on the use of DTs in healthcare in general, [109] describes the evolution and application of DTs in several areas of the healthcare sector, along with the presentation of the types of DTs utilized, such as human digital twins or DTs for specific diseases/viruses, as well as composite DTs that combine different health DTs. Aside from such DTs, DTs of organizations can be utilized to optimize the operation of healthcare-related entities, with the monitoring and maintenance of medical devices being one related use case.

In similar fashion, [110] provides a discussion on the use of CPS in the health sector, similarly suggesting the use of DTs at an organizational level, or for modelling the treatment process of individuals, leaving out the smart city elements mentioned in other works except energy and smart-grid aspects of healthcare organizations. As regards challenges, the authors identified energy flow among CPS components, integration of various systems, delay/latency and security as the most important in this sector.

Regarding more practical aspects, [111] and [112] provide two architecture proposals for implementing healthcare-related DTs. Reference [111] focuses on the provision of healthcare services for the elderly, emphasizing the role that DTs can play in this sector. The authors provide both a conceptual and a reference model for the implementation of DT healthcare systems, while also referencing the key enabling technologies for such systems. A use case scenario and a basic case study related to electrocardiography is presented, with the authors concluding that DTs have the potential to help solve bottlenecks of healthcare provision and monitoring for the elderly. Reference [112] proposes an ISO/IEEE 11073-based DT framework for healthcare and well-being services provision. The ISO/IEEE 11073 (or X73) family of standards is used as a foundation to discuss the architecture of a cloud-based system targeting individuals' health and well-being. A basic use case about encouraging physical activity is presented, along with a small-scale evaluation study.

Overall, DTs for healthcare appear to be another interesting application domain with lots of potential, due to the large penetration of personal devices like smartwatches. Moreover, several of the aspects mentioned in this subsection can be linked to other application sectors mentioned previously in this section e.g., air pollution or traffic management. As regards related challenges, the most mentioned ones are privacy and ethics, together with policy-related ones, since health data are by their nature very sensitive, followed by challenges related to implementation.

VI. CITY-SCALE DIGITAL TWINS IN PRACTICE

In this section, we present results from research projects and prototypes of DTs in cities around the world, in order to showcase the state of the art in existing solutions. We also provide a discussion on existing DT tools and products from the industry sector.

A. RESEARCH PROJECTS AND PROTOTYPES

Although city-scale DTs are still very few in number, there is a growing number of prototypes and research projects utilizing the DT approach in this context. Up until now, there have been mainly two types of urban DT prototypes; the first, focuses more on 3D representations of the built environment and aims almost exclusively at urban planning, while the second, more recent one, follows a somewhat general approach in terms of data utilized and applications developed, with additional aspects, such as integrating co-creation and collaborative activities.

Since NASA was probably the first to utilize a DT philosophy in practice, it was also one of the first to develop a large-scale DT [113] in the Langley Research Center, a 764-acre campus with over 200 facilities. Over the course of 30 years, NASA has mapped both the interior and exterior of these facilities and has curated 300 applications across a wide spectrum of domains, with 3500 users. Among such applications, NASA has used space allocation tools for personnel and equipment, achieving results such as more efficient use of office space, resulting at a reduction of 190 to 125 square feet per person. It also utilizes the data for public safety and security at its locations, along with flood vulnerability analysis, which are extremely important for this type of facilities. Maintenance and operations have also benefited from the available data, reportedly enabling NASA to handle in a more structure and quantitative manner e.g., via more number-specific public bids for maintenance at its location.

Singapore is a city that has been in the DT forefront in recent years, with Virtual Singapore [114] often cited as one of the more characteristic city-scale DTs. Singapore is among the 3 most densely populated urban areas in the world, and this is reflected to a certain extent to the applications targeted by this DT, which are mostly focused on urban planning. However, although there is an extensive and detailed 3D mapping of the urban area and it is referenced as a DT, the extent to which real-world live data are integrated to the system is not clear. A rather unique related project is the Singapore Underground [115], which focuses on further mapping the underground areas of the city for a more complete representation of the physical structures in the city.

The New South Wales DT [116] aims at offering a number of scenarios where the DT developed will be of value to the public. These include transport, urban planning, water resources, prevention of natural disasters and related climate change risks, among others, based on extensive datasets. Live data are provided for transport and air quality, while there is also a public Web interface provided for access to these data. A series of additional apps using the data of the DT focus on scenarios such as land cover or traffic congestion prediction, making this one of the most ambitious city-scale DTs.

Another DT prototype developed for use in the town of Herrenberg in Germany is presented in [102]. also discussed briefly in the previous section. Although it is much smaller scale than e.g., the NSW Digital Twin, it supports a range of different applications and puts an emphasis on collaborative aspects, by including data collected from citizens, and ways to interact with decision-makers and urban planning professionals. In this context, there is also an emphasis on the end-user interfaces available, with virtual reality options offered. In terms of scenarios, there is a focus on mobility, transport and air quality, while there is also a dimension of co-creation inserted into the project.

Regarding recent research projects focusing on urban DTs, the ongoing DUET H2020 project [117] aims at the development of DT prototypes in 3 European cities to enable transition from smart to responsive cities. As is the case with most recent DT prototypes, a set of 3D and 2D interfaces is being developed for interfacing with end users. A differentiating factor of the project is the focus on co-creation aspects, following well-established practices developed in previous smart city-related projects. The LEAD H2020 project [88] focuses on developing urban DTs for last mile logistics, with prototype implementations across 6 cities in Europe. The urban logistics planning is an interesting scenario in the urban setting, especially in the post-covid era. The SPHERE H2020 project [118] focuses more on energy aspects, aiming to provide BIM-based prototype implementations of DTs. Although the scale of the implementation is quite small compared to other urban DTs, pilots are spread across 4 European countries, representing a wide range of climate and sociocultural settings.

Although not a DT prototype per se, [37] provides useful insights into the process of designing a city-scale DT and the related steps that were utilized for the case of Cambridge in the UK. In general, the United Kingdom has been promoting the use of urban DTs relatively more aggressively than other countries. CDBB [38] (Centre for Digital Built Britain) and the associated initiative for a National DT for 'developing 'an ecosystem of connected DTs to foster better outcomes from our built environment'' are good examples of the evolution of the DT concept to encompass additional smart city aspects. Other DT-related initiatives in the UK include the project SCENE [119], which focuses on energy aspects in urban neighborhoods, with real-world deployments in Nottingham [59]. Citizens' interaction with energy-focused interfaces related to DT, reportedly produced increased awareness about energy-related issues in urban homes. Future City Glasgow [120] is another smart city initiative that is related to the utilization of DTs in this context.

Other European cities that have recently started investing in the use of DTs include Dublin [66], Zurich [66], Rotterdam [90], [121], Antwerp [122] and Helsinki [123], [124]. There are a number of other cities in Europe mentioning activity regarding DT, like Vienna [104], however most of those initiatives seem at either an early stage of consulting, or a preliminary design phase. In the case of Dublin [66], the targeted application domain is urban planning, while at the same time an interface for interaction with the citizens was demonstrated, regarding issues around urban planning and new buildings, as well as green space, allowing citizen feedback on proposed changes. The authors of [66] also voice their support for open access to urban DT models, as feedback loops with citizens. In Zurich, [105] is another example that places its focus on 3D spatial data for urban planning. In similar fashion, in [105] there is support and argumentation for DT models as open government data, instead of closed-source solutions. The authors also argue that there is a need for multiple visualization options/interfaces for DTs, in order to ease understanding of and increase support for a city DT from the citizens' point of view.

Rotterdam has the largest commercial port in Europe and is one of the 10 largest in the world, with 42Km in total length. In this sense, a DT targeting such a port can be classified as city-scale. Within this specific context, a DT [90] is under development to improve situational awareness, sustainability, and aid in autonomous ships deployment inside ports. Questions like ''how can the port be run more efficiently'', or ''how can it be safer'' can be explored through simulations utilizing the port DT. The project appears to be in development in recent years. There is an additional DT initiative [121] in the city, targeting a more common urban planning use case and having a much more open approach, with respect to the open availability of the 3D models of the city. Antwerp [122] has implemented a DT prototype, which, apart from the 3D modeling of the urban area, employs IoT data for air and noise pollution, as well as traffic information to allow for a city-scale implementation. In addition, similarly to Rotterdam (Antwerp is the second largest port in Europe), there is also an initiative to create the port's DT.

In the city of Helsinki, similarly, there appear to be several DT initiatives taking place in recent years relying on 3D modeling at a city scale, although they differ with their approach on open data. The first one focuses on tourism [123], offering an elaborate and detailed 3D model of the city available through Web and VR interfaces. The other DT initiatives [124], [125] follow the common pattern of utilizing 3D models of the city, together with semantic modelling, to allow for urban planning use cases. The models are openly available in various formats, with several levels of details offered for each building modeled, a difference with other DT projects which offer little detail inside city buildings, other than their 3D exterior and basic semantic tags.

Regarding city scale DT prototypes in China, a DT of Shanghai [126] has been developed in recent years, with 3D models of building covering an area of 3750 square kilometers. In this sense, it may be one of the largest DTs, at least in terms of area covered. As regards city-scale DTs in India, Jaipur is an example of city-scale DT using 3D modeling of urban areas to create a 3D DT of the city. However, little information is available currently in public about this specific DT. Amaravati [127] is another Indian city with an interesting urban DT referenced in recent literature, which is said to be the first example of a new city (established in 2015), with its DT being built in parallel with the actual city. However, although construction activity had initiated in previous years, currently the development of the city appears to have stalled. In the US, Boston [128] is an instance of an urban DT prototype that utilizes 3D modeling of the city buildings to enable urban planning scenarios modeling. Scenarios like simulation of the effect of high-rise buildings in surrounding areas, e.g., the effect of a skyscraper's shadow on green areas or solar energy generation, have been circulated to promote this specific DT.

In Table 2, we provide an overview of some of certain aspects, which we consider to be important, of the urban DT prototypes and projects presented in this section. More specifically, we focus on applications covered by each DT, the degree to which co-creation aspects are utilized, whether IoT data are integrated, the type of user interfaces it employs, and lastly its current status and its degree of maturity. Although the information regarding such aspects is somewhat sparse in many cases, there are some significant patterns rising from the brief presentation we attempted in this section.

More specifically, it is obvious that currently urban planning is the most popular use case scenario in city-scale DTs. It is followed by traffic and environmental monitoring, and then energy-related scenarios. There are also certain interesting scenarios tied to specific aspects, like port management and tourism, but these seem to be implemented in parallel with urban planning in such cases. One additional aspect of interest is that, currently, there are only few urban DTs that rely heavily on data from IoT and sensor networks. This comes as a bit of a surprise, given the work already dedicated to smart city aspects in recent years, and the exponential growth of the use of IoT in our daily lives. Similarly, although there is much talk about how urban DTs will revolutionize many urban application domains with the collaboration of citizens and other stakeholders, there are currently very few examples that have integrated co-creation aspects in their

TABLE 2. Comparison of a number of recent examples of city-scale DT prototypes and research projects. We focus on type of applications enabled by such systems, their openness and co-creation aspects, utilization of IoT sensors, availability of public user interfaces and current status. Some elements in the table, e.g., public UI availability, correspond to the current implementation status of the respective project/prototype.

DT Project/City	Applications	Co-creation	IoT Data	Public UI	Status/Comment
NASA [113]	Asset & Risk Management	None/limited	Unclear	N/A	Mature, many years in operation
New South Wales DT [116]	Environmental/pollution/traffic monitoring, risk and water management, urban planning	Limited, city authorities	Traffic, air, flood	3D map, Web	Mature, in operation, publicly available, several application areas, large-scale
Virtual Singapore [114]	Urban planning, environmental monitoring, traffic	Limited, city authorities	Environmental, mobility via other projects	3D map	Mature, several application areas, large-scale
Herrenberg [102]	Urban planning, environmental and pollution monitoring	Yes, citizens & stakeholders	Noise, air, traffic	3D map, Web, VR	Pilot deployment / advanced research Prototype, focus on VR interfaces
DUET [117]	Urban planning	Yes, citizens & stakeholders	Traffic, air, noise	3D map, Web	Pilot deployment / Research Prototype
SPHERE [118]	Energy in buildings	None/limited	Energy, indoor environment, weather	N/A	Small-scale pilot deployment / Research Prototype
LEAD [88]	Last-mile logistics	Yes, multiple stakeholders	Mobility	N/A	Pilot deployment / Research Prototype
Dublin [125]	Urban planning	City authorities, Universities	None/limited	3D map	Demo Prototype
Zurich [105]	Urban planning, environmental and pollution monitoring	City authorities	Traffic, environmental, energy	3D map, Web, AR	Under active development. multiple applications built
Rotterdam [90], [121]	Port Management, energy, emergencies response	Limited, city/port authorities	Port traffic and environment, traffic, energy	3D map	Under development / Prototype
Antwerp [122]	Air & Noise Pollution, traffic monitoring, urban planning	Limited, city authorities	Air, noise, traffic	3D map, Web	Prototype
Helsinki [123], [124]	Tourism, urban planning	Yes, other smart city projects	None/limited	3D map, Web, VR	Prototype
Boston [129]	Urban Planning	Limited	None/limited	3D map	Under development
Shanghai [127]	Urban Planning	None/limited	None/limited	3D map	City-scale prototype
Amaravati	Urban Planning	Led by local government	Unclear status	N/A	Unclear status
Wellington [130]	Urban Planning, traffic monitoring	Limited	Land & air traffic, parking	3D map, Web	Prototype

design and implementation, or there seems to be a lack of tools to allow for interaction with such groups. Finally, 3D maps and related Web interfaces seem to be the choice of most current implementations of user interfaces for DTs. VR is used in a few cases, like in Helsinki or in Herrenberg, while there is currently overall a quite limited selection of user interfaces targeting exclusively the citizens of the cities where these DTs are deployed.

B. EXISTING DIGITAL TWINS TOOLS AND PRODUCTS

Historically and as aforementioned, digital twin applications have been utilized primarily in the context of manufacturing systems and industrial processes. However, they are starting to declare their presence in an entirely different ecosystem as they are currently being hyped to become valuable structural elements of the smart cities. Following the paradigm of DTs in manufacturing environments, DTs in smart cities must combine 3D representations, spatial modeling, numerical and physics-based simulations of electrical and mechanical models with bidirectional data flows from sensors geographically dispersed across various IoT devices installed in buildings and machines of the city. In this section, we report on some of the more popular DT-based software solutions and products currently available.

The 3DEXPERIENCE platform by Dassault Systemes [130] is being used to create city-scale DTs like the Virtual Singapore project [114]. Its portfolio consists of several tools for designing and creating 3D models (e.g., Solidworks, CATIA), creating and simulating DTs of objects and processes (e.g., SIMULIA, DELMIA) and for managing information intelligently (e.g., NETVIBES). It provides a holistic way for urban planners to make the right decisions across all time instances.

Microsoft provides a Platform as a Service (PaaS) offering for creating knowledge graphs based on digital models of entire environments with its Azure Digital Twins platform [131]. The platform provides a JSON-like open modeling language, called Digital Twins Definition Language (DTDL), for defining the digital entities that are the representatives of the real assets in terms of their state properties, telemetry events, commands, components and semantic relationships. The data models produced by DTDL can be utilized by other Azure IoT services like IoT Plug and Play and Time Series Insights. The Azure Digital Twins explorer is used for the visualization of the live graph that represents the environment and is constructed by the models defined by DTDL. The graph can be connected with external resources for performing data processing and executing business logic. The live execution of Azure Digital Twins is synchronized with the IoT devices via the IoT Hub or custom made REST APIs.

Another platform which aspires to provide Smart City DT solutions is the HxDR platform [132] by Hexagon. HxDR is a subscription based SaaS platform that focuses mainly on providing the necessary tools and data for creating 3D replicas of urban environments. The platform contains a growing library of real world cities that can be easily manipulated and extended by the users. The software is designed to seamlessly combine heterogeneous input data from various sources, like laser scanners, aerial photography, mobile mapping data, indoor and outdoor terrestrial scan data. The user can drag and drop the relative 3D model file create by Reality Capture software and the auto mesh function of HxDR will perform the integration. However, it appears that this product targets mainly the design and development of 3D models and not IoT sensor data integration.

SmartWorldPro [133] by CityZenith is another DT tool that enables the aggregation of BIM, CAD, GIS, documents and IoT sensors in one 3D platform which is built on Unity game engine. The user can view all the systems and all the relevant data, including design, legal, financial, parcel, energy, maintenance, and security information, in one single dashboard. The platform provides users with the ability to scale up their applications from a single building to even thousands of buildings. An SDK accompanying the solution enables the extension of the existing software stack and integration with third-party applications or content. There are 2 basic offerings, a standalone version and cloud based SaaS version. Moreover, CityZenith provides a set of services that support the implementation of an end-to-end solution. These services include 3D/4D baseline asset modeling, API integration and development of custom user interfaces.

Another interesting approach is the one provided by 51WORLD and its DT city operating system, called 51City OS-POS [134]. The system utilized another company's product called 51WORLD digital twin all-element scenario platform for the integration and control of the virtual world. Thus, it incorporates information flows in various formats, like surveillance streams, building information, relational databases and IoT Sensors. In addition, it provides a visualization front-end which is capable of not only visualizing complex data in real time but also providing comparative results. 51EngineTools, a 3D model tool, transforms the models to the proper format and performs error checks. Features from image data from remote sensors can be extracted automatically and be utilized to generate urban structural elements, like buildings and roads. Furthermore, 51WORLD provides user tailored solutions which include services like traffic management, personnel and asset management, energy efficiency monitoring, and surveillance.

Twin Builder [135] is an offering by ANSYS which builds 1D models of physical systems via wiring block diagrams. What each block represents ranges from a simple numerical equation to a complex simulation in the form of a Reduced Order Model (ROM), a term that denotes a compact 3D simulation that has been stripped down to its essential parts. Even though the product is meant to support only the design, the development and the execution of simulation scenarios, it can be integrated to a live IoT platform and thus it can be fed with real IoT sensor data. Twin Builder provides a variety of ready simulation models of mechanical, electrical, electromechanical, electric and embedded systems.

Bentley Systems, which is one of the founders of the DTC, has invested heavily in DT technologies. The iTwin Platform [136] constitutes its main asset. It is an open, scalable cloud platform that provides APIs and services for building DT applications. The platform consumes engineering data from various modeling tools and creates a DT synchronized with data coming from heterogeneous sources. The visualization API allows the user to interact with iTwin in a web browser using Bentley cloud services. The synchronization between design desktop formats, like formats by Bentley or Autodesk, and the iTwin model in the cloud is executed via the iTwin Synchronized Client and the Synchronizations APIs. In addition, the platform provides APIs for the management of reality data in terms of secure storage and heterogeneity. It has been recently extended to integrate with NVIDIA Omniverse for creating a graphics pipeline for AI-enabled real-time visualization of infrastructure assets. Finally, another DT solution in Bentely Systems' portfolio is OpenCities Planner, which is a city-scale DT planning and visualizing application.

The solution provided by Deloitte, called Optimal Reality [137], is a DT capability, based on simulation techniques at first utilized in Formula One racing. The platform ingests real time data and produces a dynamic model, which can be accessed by as single Web portal. The product focuses mainly on delivering insights in air traffic and road network and incident scenarios.

ESRI is a leading player in GIS and spatial mapping software industry and has developed ArcGIS [138], which is a framework for developing and integrating DTs. It provides integration of GIS, Reality Capture, and BIM data with real time IoT feeds, and AI algorithms. The ArcGIS Platform is offered as a PaaS, and contains data hosting and content management services. The user can create and manage new content by utilizing the provided tools and applications, or can use native or third-party open source APIs for custom mapping and creating spatial applications, which have access to data and services of the platform. Finally, all the applications can interact with a set of ready-to-use location services (e.g. routing service, geocoding service, elevation service etc.) via a REST API.

IES company has launched Intelligent Communities Lifecycle (ICL) Digital Twin [139], which constitutes a single platform that integrates 3D models, with a physics based simulation engine, real-time data, and AI data algorithms. The platform scales up from a single building to an entire city producing data driven insights on energy, operational, carbon, and capital savings. It is based on a set of interconnected tools that share a common database. More specifically, these tools are the Intelligent Community Design (iCD), which comprises 3D Urban design and early stage master planning, the Virtual Environment (VE), which is a building analytics platform, the iSCAN, which is a tool created for collecting and analyzing time-series data from different sources (buildings, utility portals, databases, IoT sensors), and the Intelligent Virtual Network (iVN), which is a networking and management tool.

Manufacturing sector is undoubtedly one of the pioneers in embracing DT solutions. General Electric (GE) follows closely this trend [140] mainly by offering different solutions for different use cases. For modeling components, critical assets or systems of assets the SmartSignal and the Asset Performance Management (APM) solutions can be utilized to create an Asset Digital Twin. Technologies like GE's ADMS, GIS, and AEMS can be used to provide a connected view of end-to-end live networks of assets, which are identified as Network Digital Twins. In addition, the development and the operation of a Process Digital Twin can identify the optimal process for manufacturing a product, given a specific manufacturing environment. All in all, GE provides a quite mature solution that is integrated into its Predix IoT platform.

Following the same footsteps, Siemens has established a strong position in the field of DTs [141] in the manufacturing and process industry. The company's open cloud based IoT platform, called Mindspere, is capable of hosting DT applications, and feeding them with data from products, systems or factories. The platform belongs to a larger portfolio of software, development environments, and services, which is named Xcelarator. Except for Mindsphere, the portfolio includes tools for mechanical design and simulation, like NX, Product Lifecycle Management software which is the cornerstone of the DT, such as Teamcenter, software that allows to create cloud-based 2D/3D representation of the factory floor, like Intosite, and another portfolio, Technomatrix, that helps in the digitization of the manufacturing process.

Moving onto a larger scale, Descartes Labs have launched the first ever cloud-based analytics geospatial platform [142] which aspires to provide a DT of the physical world. The platform exposes three basic components: the data refinery, which contains over 15 petabytes of geospatial data from public and private sources, the workbench, which is a Python compatible modelling environment, and the applications, which are package analytics solutions combining data, analysis and visualization. It, thus, enables forecasting capabilities over various application domains and industries, like mining, shipping, agriculture, energy and financial services.

Table 3 illustrates the comparison between the various digital solutions tools and application described above with regard to key components, such as pricing and availability, simulation capabilities, integration with IoT sensors, data management options, and applications/prototypes implemented. It is evident that there is already a critical mass of software platforms available to developers to implement DT-based solutions. The platforms support scenarios linked to city-scale DTs, with urban planning being the urban use-case supported by almost all of them. One can also remark that several of the prototypes/projects mentioned in Table 2 are implemented using some of these platforms, and are not based on custom software solutions. Furthermore, the majority of the companies developing such tools are part of initiatives such as DTC and IDTA; we thus expect standardization efforts to make considerable progress in the coming years through such wide industry support. We also expect open source solutions for DTs to gradually start making their appearance, based on the existence of such standards.

VII. OPEN CHALLENGES AND DISCUSSION

A. OPEN CHALLENGES FOR DT IN SMART CITIES

In this section, we attempt to briefly present the open challenges of city-scale DTs as derived from the discussion of the application domains presented in the previous sections, and then offer a more general perspective regarding this area.

1) DATASETS AND DATA SOURCES

Although we have been discussing data-enabled cities and digital marketplaces for smart cities for quite some time, there is still much to be desired in terms of data available for use by city-scale DTs. Since many of the recent technological advancements upon which DTs have been based, such as ML, Deep Learning and Big Data, rely on the availability and quality of data, this is a recurring theme when discussing real-world DT implementations. On top of that, ownership of urban datasets is another important dimension, adding further complexity to this issue. As [35] emphasizes, many times what is difficult is not to find a meaningful scenario in which to design and implement a city-scale DT, but actually finding the required data and setting up the respective collaborations and links between multiple stakeholders to provide the data that will be fed into the DT. The ownership of data in specific industrial settings appears to be much less contentious, and this could, to a certain extent, also explain why there is a large gap between the rate of adoption of DTs in smart manufacturing and that of applications in a city context in recent years. Data in cities might be owned by the city itself or by different stakeholders of the city ecosystem, including academia and private companies, implementing city projects, and is furthermore associated with costs for data quality, anonymization, etc.

We should also have in mind that data requirement for DTs in urban settings can have requirements that are quite different to their counterparts in industrial settings. Whereas in industry there may e.g., be scenarios that require sampling rates in the area of several kHz, in cities measurements could

TABLE 3. **Comparison of the DT tools and solutions available currently, as regards features such as pricing and availability, simulation capabilities, integration with IoT sensors, data management options and applications/prototypes implemented using such solutions.**

DT Tools and Products	Pricing	3D Content Creation	Simulation	IoT Integration	Data Management	Applications/Prototypes
Dassault 3DEXPERIENCE [131]	Commercial/ Demo available	Yes	Yes	Yes	Yes	Urban Planning (Singapore, Jaipur)
Azure Digital Twins [132]	Commercial / Free Trial	No	Yes	Yes (Azure IoT Hab, REST APIS)	Yes	Energy, comfort, monitoring of buildings, traffic/fleet management, urban planning
HxDR [133]	Commercial (to be released)	Ready 3D City Library, Auto mesh from Reality Capture point cloud, import mesh	No	No (planned)	No	Energy, comfort, monitoring of buildings, Urban planning
SmartWorldPro [134]	Commercial (standalone, SaaS) / demo available	Support the import of various 3D data formats, Ready 3D City Library	No	Yes	No	Urban Planning (Amaravati), Energy comfort, monitoring of buidlings
51City OS-POS [135]	Free (Community Edition) / Commercial	Ready 3D City Libraries	Yes	Yes	Yes	Energy, comfort, monitoring of buildings (Jiangbei New District, Shanghai), Urban planning, Water Management (Yunnan Sanhu Smart Water)
Ansys Twin Builder [136]	Commercial	No	Yes	Third party platforms	No	Pollution Control
Bentley iTwin, ContextCapture, OpenCities Planner [137]	Commercial	Yes	Yes	Yes	Yes	Urban Planning (Helsinki, Dublin)
ESRI ArcGIS [139]	Commercial / Free Trial	Yes	No	Yes	Yes	Urban Planning (Boston), Port Management (Rotterdam), Traffic, Mobility Management
IES Digital Twins [140]	Commercial / Free Trial	Yes	Yes	Yes	Yes	Energy, comfort, monitoring of buildings (NTU Singapore), Urban Planning
Siemens Digital Twin [142]	Commercial	Yes	Yes	Yes	Yes	Urban Planning, Traffic, Mobility Management
DescartesLabs [143]	Commercial	No	No	No	Yes	Urban Planning
Zero Gravity [144] [139]	Commercial	Yes	No	Yes	No	Urban Planning, Traffic, Mobility Management, Energy Monitoring
GE - Predix IoT [141]	Commercial	No	Yes	Yes	Yes	Infrastructure monitoring

arrive at rates of several Hz, or even slower. However, this also implies that such values could be produced by a very large number of components that are spread throughout a large area, that are prone to faults, or that are supposed to operate for large periods unattended or uncalibrated, etc. The issues of the quality of data and data maintenance become very important in such settings, especially when we consider that a city-scale DT should utilize such data to produce a reliable global view of a specific application domain at a large scale. In this context, mechanisms for ML-based sensor calibration of low-cost sensors and data imputation should prove to be valuable allies towards having datasets of reasonable quality in cities.

2) DATA STANDARDS AND INTEROPERABILITY

This is one area where all previous surveys in the DT domain agree, regardless of specific application focus; at the moment, there is an urgent need for common standards to be defined, in order to accelerate DT implementation and rollout, together with interoperability between them and other existing systems, like smart city platforms. It is also clear that the industry is reacting to this need, as is evident by the formation of the Digital Twin Consortium [50] (DTC), as well as the Industrial Digital Twin Association [51]. From the side of international standardization bodies, we are also seeing the activities of ISO/IEC JTC 1/SC 41 [47] in this space, indicating again the great interest in tackling this open challenge in the DT domain. Towards this direction, DTC also promises to create a library of reference implementations for DTs, that could potentially aid towards resolving interoperability issues faster.

In more practical terms, we are also beginning to see standards affecting aspects of implementing city DTs, like mobility, to be announced, e.g., such as in the case of the Mobility Data Specification [80]. Specifically for city-scale DTs, CDBB is an example of another public initiative to help push forward the use of DTs at a national scale, which could also help to accelerate the release and adoption of related standards, since in this domain it is imperative that a large number of parties usually from both the public and the private sector must collaborate in order to implement a DT.

3) CO-CREATION AND COLLABORATION WITH STAKEHOLDERS

As pointed out in multiple instances in this work, city-scale DTs require a number of different actors and stakeholders to be involved in order for them to operate. The fact that such parties belong to communities with different backgrounds, structures and organization, in many cases precludes a top-down approach to designing and implement such DTs. This fact has been known to the smart city community for many years and has translated to the broad use of co-creation mechanisms when collaborating with such communities in the case of smart city implementations that preceded city-scale DTs. We believe that to a great extent co-creation of use cases, tools and procedures for using such DTs is necessary, especially during the current period, since, as pointed out in Section II, the overall definition of DT is still under development, while there is also a lack of established methodologies and tools. As examples of this approach, the LEAD project [88] utilizes living labs methodologies to engage with the logistics community, while DUET [117] engages with communities in 3 European cities emphasizing co-creation with them in several use-cases.

For allowing a deeper collaboration with stakeholders such as citizens, the DT community could also explore the use of tools and methodologies at the disposal of the smart city community like crowdsourcing, participatory sensing and citizen science. Such dimensions could work on multiple planes simultaneously by improving data quality and area coverage, engaging actively these stakeholders and making them a part of the design of the DT, etc.

4) MAKE DATA MEANINGFUL AND ACCESSIBLE TO CITY STAKEHOLDERS

Continuing from the previous open challenge, in order to get the continuous support of the different stakeholders involved in city-scale DTs, such groups need to informed about the capabilities and results produced by the DT, as well as be kept engaged with it. In other words, another open challenge is how to make city-scale DT data available to the public and more comprehensible, in order to better understand its potential and whether it actually delivers public value. Up until now, the vast majority of public UIs of such DTs has been based on 3D maps through dedicated applications or dedicated websites, since in many cases this part is already available from the DT themselves, due to the fact that it a digital shadow of the real world. Some prototypes have taken this concept a bit further, like in the case of the DT prototype in Herrenberg [102] or Helsinki [123], offering VR or AR views of the DT.

However, we feel that the challenge of interfacing with the DT end-users is still open in many cases. In order for city DTs to improve governance and provide stakeholders with the ability to take well-informed decisions, this also depends on the ability to communicate effectively the benefits of the DT approach itself, which is not served equally well in all use-case scenarios by a UI based on 3D representations. In fact, we believe that in certain cases it can have adversary effects, since the scale of the DT alone can be intimidating. One other important element could be the use of additional interactivity in DT user interfaces, inviting end-users to experiment with potential what-if scenarios in urban areas, allowing them to better understand the potential of the DT and the added value it brings to communities and local authorities, since such scenarios are at the core of the DT design and philosophy.

5) PRIVACY, SECURITY AND ETHICS

Another important dimension in city-scale DTs is privacy, together with security and associated ethical challenges. This dimension was already critical for smart cities, and it is no surprise that it is an open challenge for city-scale DTs as well. As examples of associated privacy risks, in city-scale DTs related to traffic management, there is a real danger of abusing location-sensitive data produced from vehicles where deanonymizing them would mean tracking the location of individuals. Frameworks like GDPR [144] in Europe provide a strong regulation foundation, upon whose guidelines more specific privacy-protecting implementations can be built. Distributed Ledger Technologies (DLT), like Blockchain, could be one tool that potentially helps towards this direction. We have also seen prototypes utilize approaches like Federated Learning [96] to decentralize ML-related processes and enhance privacy aspects.

Moreover, there is the additional ethics aspect of city-scale DTS, which is also linked to transparency and accountability. For such a DT, it should be clear that it adds public value, since a number of communities and stakeholders are typically involved in its operation. If such end-users are not convinced of the benefits it provides and whether it upholds privacy and security standards, it could be met with indifference, or even hostility. Furthermore, the DTC is developing best practices for security, privacy and trustworthiness; such initiatives can further accelerate DT implementation, since the privacy-related design and implementation aspects can be considerably complex, especially for systems of such size and complexity.

6) COST AND BENEFITS OF A DT's IMPLEMENTATION

One challenge which is not often brought up in the relevant discussion is the hidden costs in implementing in practice a DT for several application domains at scale. This could be due to e.g., the need to install new sensing infrastructure, lack of sufficient existing infrastructure/network documentation, or simply inability to change the current situation without re-installing everything. At the moment, city-scale DTs have many proposed use-cases, but in order to translate the surrounding hype to reality there is also a need to see how they can be applied in practice in multiple application domains. In this sense, guidelines and examples made available by the DTC and similar stakeholders could be crucial for DT designers in order to understand current technological limitations and requirement from a deployment and financial viewpoint. As DTC also suggests, such initiatives could help reduce the risk of capital projects through the dissemination of such peer use cases and also having better access to pools of experts. Moreover, results from projects like LEAD [88] and DUET [117] are important in order to get ''blueprints'' for city-scale DTs specifically.

7) SCALE AND COMPLEXITY

One aspect that sets city-scale DTs apart from other types of DTs, is of course their potential scale, which combined with the aforementioned open challenges makes it even more complex and challenging. This can be true even in scenarios where a DT can be focused on a specific application subset or part of an urban area, especially in cases like e.g., the Rotterdam port DT [90], which is essentially a city within a city. The derived complexity in such systems is another differentiating factor, since the underlying IoT/sensor infrastructure often comprises a multitude of different technologies in order to respond e.g., to the requirements of each area, or simply because deployments have been done during several periods. Cities are living ecosystems that can potentially evolve at a rapid pace; we are even witnessing city-scale DTs being built before the actual city materializes, like in the case of city projects in India. Existing research from smart cities to a great extent provides answers to such issues, however it remains to be seen how all of this affects the actual value produced by the DT, and to what extent the requirements of the DT application are going to affect the scale and complexity of such infrastructure as well.

8) DISTRIBUTED INTELLIGENCE AND EDGE COMPUTING

An additional aspect related to the utilization of DTs at an urban scale is that the more computing and storage resources are placed closer to the information sources, e.g., sensing infrastructure, the lesser burden is placed on communications infrastructures, e.g., less need to send sensor measurements or offload computing tasks to the cloud, which in turn means that DT models can converge to the real-world behaviour in a much faster time period, while also utilizing fewer resources. Of course, this may have the side-effect with respect to federated knowledge (federated AI), due to the additional information needed to be interchanged across the node hierarchy for training and learning purposes. But DTs can bring the support to correctly plan how much intelligence has to be placed in the far edge and edge components and how much in the core part. We can presume that this will partially depend on the dynamicity of the urban services deployed. E.g., a DT targeting traffic management will have significantly different requirements compared to a waste management one.

Up until now, the majority of deployed DTs uses architectures mainly targeting cloud-based processing and storage, or utilize centralized DT islands. As we are currently witnessing edge computing capabilities advance at a brisk pace, based to a great extent on ML hardware acceleration capabilities being added to embedded systems (e.g., in electric vehicles or on embedded hardware prototyping platforms targeting computer vision-related applications), we believe that DT implementations utilizing edge computing as a core architectural component will begin to become more common. This is also in line with the requirements for increased privacy and security in such systems, as mentioned above, since they reduce the need to move potentially sensitive data across the system hierarchy.

9) LATENCY

Depending on the specific DT sub-domain, communication latency can be an issue that affects performance considerably. E.g., in traffic management, healthcare, or disaster response, and depending on the specific application scenario, data should be propagated as quickly as possible. Current smart city sensing infrastructure often uses sampling rates of several seconds or minutes, using low-bandwidth wireless networks that were not designed with low latency in mind. The situation in smart manufacturing in many cases is currently not radically different either. Technologies like 5G promise to aid in tackling this issue decisively, however existing infrastructure that supports current DTs should likely be upgraded to support a transition to low latency capabilities, or be paired with such technologies to improve them in such aspects. In this sense, it is worth to highlight that the distributed intelligence and edge computing approaches mentioned above can also contribute to cope with the latency by reducing the overhead when processing the collected data, thus allowing to predict the most suitable action for overcoming or mitigating the degradation of the services provided by a smart city.

10) SKILLS

The deployment of a DT in a city requires an upskilling of the entire city ecosystem, so as to be possible to reap the most out of it. First and foremost, this need is prevalent for city officials that need to first understand, then prioritize their interventions, and then procure and implement the DT deployment in an open and interoperable way. Secondly, there is a need for upskilling the local SME world, so as to be possible to participate in the DT instigated city collaboration scheme and benefit from it. Finally, there is a need for developing adequate digital skills to the general public in order to be possible to make use of the DT and its services. The academic and research world are needed in this process so as to establish adequate curricula for vertical learning paths offering advanced digital skills to the aforementioned city ecosystem target groups.

11) 5G TECHNOLOGIES AND DTs

We should also mention the rapid advancements of 5G technologies and how they can help to deal with the aforementioned challenges. Currently, their use in smart manufacturing is one of the major arguments for their adoption by the industry and a major factor in their design from the beginning. In this context, [145] is a white paper that discusses the ways 5G technologies can support the implementation of Industry 4.0 concepts in practice. Regarding the relation between 5G for DTs there are 2 sides: DTs can help in deploying 5G faster, while 5G can help with some of the challenges that DTs face. Since 5G networks, at least in urban areas, will be implemented using denser networks deployments than previous technologies such as 4G, this requires a more complex planning process. Having this in mind, [146] discusses the utilization of DTs to support the gradual deployment of 5G services. Looking further ahead into the future, [147] discusses a DT-enabled 6G vision.

Regarding 5G technologies' integration within city-scale DTs, they could help decisively with challenges such as latency, scale and complexity, as well as with providing a stable, standards-based, technological foundation within the current smart city landscape that features an abundance of competing solutions aiming to win the respective market. Furthermore, private 5G networks can co-exist with current LPWAN solutions to enable an even more scalable and flexible implementation in challenging settings, such as the ones in urban areas, allowing further data granularity and model fidelity for more accurate city-scale DTs.

B. DISCUSSION

Getting back to the 3 Research Questions stated in Section I of this work and specifically RQ1, one last challenge not included above is the challenge of the definition of the city-scale DT; similarly to the question of what is a smart city, it seems that we have to go through a number of repetitions in the evolution of the DT concept to get a better grasp as regards which are the possibilities, the limitations and the opportunities in creating a city-scale DT. As is evident from the analysis in previous sections, DTs have evolved in several ways, and we can expect with great confidence that they will continue to evolve in order to encompass new application domains and aspects. Moreover, since many different research and scientist communities "define" such aspects from their own point of view, it will take a while for these dimensions to synthesize and converge to more uniform definitions.

Regarding RQ2 and which are the most popular DT application fields in cities, thus far urban planning appears to be the option chosen by the majority of the prototypes and projects presented in this work. Even in the case of having multiple domains tackled by the same DT, e.g., the NSW DT [116], urban planning is also present there as well. As for the rest of the application domains, traffic management and environmental monitoring seem to be the next most popular option, although they are far behind in popularity. However, we expect that the popularity gap between urban planning and the rest of the fields discussed in this work will close in the coming years, with applications in energy and electric vehicles also presenting very interesting prototypes in recent years.

Regarding RQ3 and the open challenges discussed previously in this section, it appears that standardization, interoperability and data quality are the issues brought up more often by recent research. This makes sense, since they are among the most important parts in the implementation chain of city DTs. However, as we have seen in smart cities as well, technology is not a silver bullet and is only part of the equation, i.e., we believe that the open challenges related to the stakeholders and communities involved should not be relegated after the technological ones.

Overall, it appears that city-scale DTs are currently at a crossroads, and in order to turn from hype to reality there will be a period of experimenting with possible use case scenarios and prototypes until a set of more stable solutions and application is found, similar to how the DTs themselves function as well. In this context, we believe that the DT community and relevant stakeholders should focus on communicating the actual benefits of DTs in terms of making informed decisions to the communities involved. There is also the issue of the balance between actual costs and benefits delivered to urban communities, which an important part of the city-scale DT equation.

VIII. CONCLUSION

In this work, we attempted to survey the application of the DT concept during recent years, and especially within the context of the smart city. DTs present a series of advantages that together with existing smart city data and technologies could have a transformative effect on how cities are run, especially as regards urban planning, mobility and energy, to name a few dimensions. Although the use of DTs seems to be flourishing in the smart manufacturing and industrial domain, their application in smart cities appears to still be at a preliminary stage. However, there are already several examples of city-scale DT prototypes tackling different application domains and there is clearly a lot of potential for DT-based solutions in smart cities. We have identified a series of these domains and categorized an extensive set of recent DT-based related approaches, revealing the current trends and dynamics in this field. At this point in time, there still seems to be a fluidity even in the definition of the DT as a general term, and even more in terms of technologies utilized and how they are applied. This seems to be further accentuated by the fact that the various communities that have so far used DT-based approaches in a city context tend to define what the city DT concept refers to, based on their scientific discipline background, which, in our opinion, corresponds to just one piece of the city-scale DT puzzle.

Regarding other characteristic differences between DTs in smart manufacturing and those in smart cities, one fundamental difference is the scale: since smart cities are essentially systems of systems, the complexity and heterogeneity of city-scale DTs can be orders of magnitude greater than their industrial counterparts. In this sense, the existing challenges in other types of DTs are further intensified, while there are other, more unique, aspects that need to be catered for by the research community and the industry. There is also a multitude of end-user types and entities that are potentially involved in the design, implementation and utilization of smart city DTs, which is not the case in the smart manufacturing domain where usually more well-defined groups of users utilize them in relatively stable scenarios. This also leads to additional challenges in terms of (potentially) public interfaces and visualization for smart city DTs, due to the fact that such DTs should also exhibit their actual value to end-users as part of their overall lifecycle.

Related to such aspects, we have also provided a discussion of current open research challenges in DTs for smart cities. Apart from the abovementioned aspects, given that this domain by design involves the participation of numerous citizen communities, together with businesses and multiple administrative levels, it becomes evident that established methodologies that are utilized by the smart city community, like co-creation, should be utilized by the DT community to ease the successful design, development and deployment of DT-based solutions in this context. Other important open challenges center around datasets and data sources, the use of data standards and interoperability, together with privacy, security and ethics. The vast majority of these issues originate from the simple fact that these are large systems of systems, that involve the collaboration of multiple parties and the use of numerous technologies. However, we are optimistic that such initial obstacles will be gradually overcome, and that DTs will become a part of the smart city landscape in the near future.

REFERENCES

[1] D. Serpanos and M. Wolf, "Industrial Internet of Things," in *Internet-of-Things (IoT) Systems*. Berlin, Germany: Springer, 2018, pp. 37–54.

[2] C. Koulamas and A. Kalogeras, "Cyber-physical systems and digital twins in the industrial Internet of Things [cyber-physical systems]," *Computer*, vol. 51, no. 11, pp. 95–98, Nov. 2018.

[3] Q. Qi, F. Tao, T. Hu, N. Anwer, A. Liu, Y. Wei, L. Wang, and A. Y. C. Nee, "Enabling technologies and tools for digital twin," *J. Manuf. Syst.*, vol. 58, pp. 3–21, Jan. 2021.

[4] General Electric Digital. *Industrial Digital Twins: Real Products Driving $1B in Loss Avoidance*. Accessed: May 2021. [Online]. Available: https://www.ge.com/digital/blog/industrial-digital-twins-real-products-driving-1b-loss-avoidance

[5] *Marketsandmarkets Report, Digital Twin Market Worth $48.2 Billion by 2026*. Accessed: May 2021. [Online]. Available: https://www.marketsandmarkets.com/pressreleases/digital-twin.asp

[6] A. Rasheed, O. San, and T. Kvamsdal, "Digital twin: Values, challenges and enablers from a modeling perspective," *IEEE Access*, vol. 8, pp. 21980–22012, 2020.

[7] M. Grieves, "Digital twin: Manufacturing excellence through virtual factory replication," Tech. Rep., 2014, pp. 1–7, vol. 1.

[8] European Commission. *Community Research and Development Information Service (CORDIS)*. Accessed: Jun. 2021. [Online]. Available: https://cordis.europa.eu

[9] *Siemens, Apollo 13: The First Digital Twin*. Accessed: May 2021. [Online]. Available: https://blogs.sw.siemens.com/simcenter/apollo-13-the-first-digital-twin/

[10] M. Shafto, M. Conroy, R. Doyle, E. Glaessgen, C. Kemp, J. LeMoigne, and L. Wang, "Modeling, simulation, information technology & processing roadmap," *Nat. Aeronaut. Space Admin.*, vol. 32, pp. 1–38, 2012.

[11] J. Lee, E. Lapira, B. Bagheri, and H.-A. Kao, "Recent advances and trends in predictive manufacturing systems in big data environment," *Manuf. Lett.*, vol. 1, no. 1, pp. 38–41, 2013.

[12] J. Ríos, J. C. Hernandez, M. Oliva, and F. Mas, "Product avatar as digital counterpart of a physical individual product: Literature review and implications in an aircraft," in *Proc. ISPE CE*, 2015, pp. 657–666.

[13] A. Stefano, D. Blagoj, and C. Max, "Destination earth: Survey on 'digital twins' technologies and activities, in the green deal area," Publications Office Eur. Union, Luxembourg, Tech. Rep. JRC122457, 2020.

[14] W3C. (Apr. 2020). *Web of Things (WoT) Architecture, W3C Recommendation*. Accessed: May 2021. [Online]. Available: https://www.w3.org/TR/2020/REC-wot-architecture-20200409

[15] IBM. *What is a Digital Twin*. Accessed: May 2021. [Online]. Available: https://www.ibm.com/topics/what-is-a-digital-twin

[16] IBM. *Digital Twin Technologies for High-Performance Manufacturing*. Accessed: May 2021. [Online]. Available: https://www.ibm.com/downloads/cas/KX8A3MWX

[17] (2018). *The Gemini Principles. Report of Cambridge: Centre for Digital Built Britain*. Accessed: May 2021. [Online]. Available: https://www.cdbb.cam.ac.uk/DFTG/GeminiPrinciples

[18] R. Saracco, "Digital twins: Bridging physical space and cyberspace," *Computer*, vol. 52, no. 12, pp. 58–64, Dec. 2019.

[19] R. Rosen, G. Von Wichert, G. Lo, and K. D. Bettenhausen, "About the importance of autonomy and digital twins for the future of manufacturing," *IFAC-Papers OnLine*, vol. 48, no. 3, pp. 567–572, 2015.

[20] E. A. Lee, "Cyber-physical systems-are computing foundations adequate," in *Proc. Position Paper NSF Workshop cyber-Phys. Syst., Res. Motivat., Techn. Roadmap*, vol. 2. Princeton, NJ, USA: Citeseer, 2006, pp. 1–9.

[21] E. A. Lee, "Cyber physical systems: Design challenges," in *Proc. 11th IEEE Int. Symp. Object Compon.-Oriented Real-Time Distrib. Comput. (ISORC)*, May 2008, pp. 363–369.

[22] V. K. Sehgal, A. Patrick, and L. Rajpoot, "A comparative study of cyber physical cloud, cloud of sensors and Internet of Things: Their ideology, similarities and differences," in *Proc. IEEE Int. Adv. Comput. Conf. (IACC)*, Feb. 2014, pp. 708–716.

[23] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[24] D. Serpanos, "The cyber-physical systems revolution," *Computer*, vol. 51, no. 3, pp. 70–73, Mar. 2018.

[25] H. Boyes, B. Hallaq, J. Cunningham, and T. Watson, "The industrial Internet of Things (IIoT): An analysis framework," *Comput. Ind.*, vol. 101, pp. 1–12, Oct. 2018.

[26] A. P. Kalogeras, H. Rivano, L. Ferrarini, C. Alexakos, O. Iova, S. Rastegarpour, and A. A. Mbacké, "Cyber physical systems and Internet of Things: Emerging paradigms on smart cities," in *Proc. 1st Int. Conf. Societal Autom. (SA)*, Sep. 2019, pp. 1–13.

[27] F. Tao and M. Zhang, "Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing," *IEEE Access*, vol. 5, pp. 20418–20427, 2017.

[28] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital twin in industry: State-of-the-art," *IEEE Trans. Ind. Informat.*, vol. 15, no. 4, pp. 2405–2415, Apr. 2019.

[29] T. Y. Melesse, V. Di Pasquale, and S. Riemma, "Digital twin models in industrial operations: State-of-the-art and future research directions," *IET Collaborative Intell. Manuf.*, vol. 3, no. 1, pp. 37–47, Mar. 2021.

[30] M. Liu, S. Fang, H. Dong, and C. Xu, "Review of digital twin about concepts, technologies, and industrial applications," *J. Manuf. Syst.*, vol. 58, pp. 346–361, Jan. 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0278612520301072

[31] M. Schluse, M. Priggemeyer, L. Atorf, and J. Rossmann, "Experimentable digital twins—Streamlining simulation-based systems engineering for industry 4.0," *IEEE Trans. Ind. Informat.*, vol. 14, no. 4, pp. 1722–1731, Apr. 2018.

[32] A. P. Fournaris, A. Komninos, A. S. Lalos, A. P. Kalogeras, C. Koulamas, and D. Serpanos, "Design and run-time aspects of secure cyber-physical systems," in *Security and Quality in Cyber-Physical Systems Engineering*. Berlin, Germany: Springer, 2019, pp. 357–382.

[33] M. Eckhart and A. Ekelhart, "A specification-based state replication approach for digital twins," in *Proc. Workshop Cyber-Phys. Syst. Secur. Privacy*, Jan. 2018, pp. 36–47.

[34] *United Nations Department of Economic and Social Affairs*. Accessed: Jun. 2021. [Online]. Available: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

[35] L. Hemetsberger. *Cities & Digital Twins: From Hype to Reality*. Accessed: Jun. 2021. [Online]. Available: https://oascities.org/three-key-challenges-towards-digital-twin-adoption-at-scale/

[36] L. Sanchez, L. Muñoz, J. A. Galache, P. Sotres, J. R. Santana, V. Gutierrez, R. Ramdhany, A. Gluhak, S. Krco, E. Theodoridis, and D. Pfisterer, "SmartSantander: IoT experimentation over a smart city testbed," *Comput. Netw.*, vol. 61, pp. 217–238, Mar. 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1389128613004337

[37] T. Nochta, L. Wan, J. M. Schooling, and A. K. Parlikad, "A socio-technical perspective on urban analytics: The case of city-scale digital twins," *J. Urban Technol.*, vol. 28, nos. 1–2, pp. 263–287, 2020, doi: 10.1080/10630732.2020.1798177.

[38] *Cambridge CDBB: Centre for Digital Built Britain—National Digital Twin Initiative*. Accessed: Jun. 2021. [Online]. Available: https://www.cdbb.cam.ac.uk/

[39] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108952–108971, 2020.

[40] Q. Qi and F. Tao, "Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison," *IEEE Access*, vol. 6, pp. 3585–3593, 2018.

[41] B. R. Barricelli, E. Casiraghi, and D. Fogli, "A survey on digital twin: Definitions, characteristics, applications, and design implications," *IEEE Access*, vol. 7, pp. 167653–167671, 2019.

[42] *White Paper: Digital Twins for the Built Environment*, Inst. Eng. Technol. (IET), London, U.K., 2018. [Online]. Available: https://www.theiet.org/media/4719/digital-twins-for-the-built-environment.pdf

[43] R. Minerva, G. M. Lee, and N. Crespi, "Digital twin in the IoT context: A survey on technical features, scenarios, and architectural models," *Proc. IEEE*, vol. 108, no. 10, pp. 1785–1824, Oct. 2020.

[44] I. Errandonea, S. Beltrán, and S. Arrizabalaga, "Digital twin for maintenance: A literature review," *Comput. Ind.*, vol. 123, Dec. 2020, Art. no. 103316. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0166361520305509

[45] T. R. Wanasinghe, L. Wroblewski, B. K. Petersen, R. G. Gosine, L. A. James, O. De Silva, G. K. I. Mann, and P. J. Warrian, "Digital twin for the oil and gas industry: Overview, research trends, opportunities, and challenges," *IEEE Access*, vol. 8, pp. 104175–104197, 2020.

[46] E. Shahat, C. T. Hyun, and C. Yeom, "City digital twin potentials: A review and research agenda," *Sustainability*, vol. 13, no. 6, p. 3386, Mar. 2021. [Online]. Available: https://www.mdpi.com/2071-1050/13/6/3386

[47] *ISO/IEC JTC 1 Information Technology*. Accessed: Jun. 2021. [Online]. Available: https://www.iso.org/committee/45020.html

[48] *Joint Advisory Group (JAG) Group on Emerging Technology and Innovation (JETI)*. Accessed: Jun. 2021. [Online]. Available: https://jtc1info.org/technology/advisory-groups/jeti/

[49] *Automation Systems and Integration Digital Twin Framework for Manufacturing—Part 1: Overview and General Principles*, Standard ISO/DIS 23247-1, 2020. Accessed: Jun. 2021. [Online]. Available: https://www.iso.org/standard/75066.html

[50] *Digital Twin Consortium*. Accessed: Jun. 2021. [Online]. Available: https://www.digitaltwinconsortium.org/

[51] *Industrial Digital Twin Association*. Accessed: Jun. 2021. [Online]. Available: https://idtwin.org/en/

[52] H. van der Valk, H. Hasse, F. Möller, M. Arbter, J.-L. Henning, and B. Otto, "A taxonomy of digital twins," in *Proc. AMCIS*, 2020.

[53] M. M. Rathore, S. A. Shah, D. Shukla, E. Bentafat, and S. Bakiras, "The role of AI, machine learning, and big data in digital twinning: A systematic literature review, challenges, and opportunities," *IEEE Access*, vol. 9, pp. 32030–32052, 2021.

[54] M. Austin, P. Delgoshaei, M. Coelho, and M. Heidarinejad, "Architecting smart city digital twins: Combined semantic model and machine learning approach," *J. Manage. Eng.*, vol. 36, no. 4, Jul. 2020, Art. no. 04020026.

[55] V. Todeschi, R. Boghetti, J. H. Kämpf, and G. Mutani, "Evaluation of urban-scale building energy-use models and tools—Application for the city of Fribourg, Switzerland," *Sustainability*, vol. 13, no. 4, p. 1595, Feb. 2021.

[56] E. O'Dwyer, I. Pan, R. Charlesworth, S. Butler, and N. Shah, "Integration of an energy management tool and digital twin for coordination and control of multi-vector smart energy systems," *Sustain. Cities Soc.*, vol. 62, Nov. 2020, Art. no. 102412. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2210670720306338

[57] A. Francisco, N. Mohammadi, and J. E. Taylor, "Smart city digital twin–enabled energy management: Toward real-time urban building energy benchmarking," *J. Manage. Eng.*, vol. 36, no. 2, Mar. 2020, Art. no. 04019045.

[58] A. E. Onile, R. Machlev, E. Petlenkov, Y. Levron, and J. Belikov, "Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review," *Energy Rep.*, vol. 7, pp. 997–1015, Nov. 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352484721000913

[59] L. Rodrigues, M. Gillott, J. Waldron, L. Cameron, R. Tubelo, R. Shipman, N. Ebbs, and C. Bradshaw-Smith, "User engagement in community energy schemes: A case study at the trent basin in Nottingham, UK," *Sustain. Cities Soc.*, vol. 61, Oct. 2020, Art. no. 102187. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2210670720301748

[60] A. Zaballos, A. Briones, A. Massa, P. Centelles, and V. Caballero, "A smart campus' digital twin for sustainable comfort monitoring," *Sustainability*, vol. 12, no. 21, p. 9196, Nov. 2020. [Online]. Available: https://www.mdpi.com/2071-1050/12/21/9196

[61] C. Ye, L. Butler, C. Bartek, M. Iangurazov, Q. Lu, A. Gregory, M. Girolami, and C. Middleton, "A digital twin of bridges for structural health monitoring," in *Proc. 12th Int. Workshop Struct. Health Monit.* Stanford, CA, USA: Stanford Univ., 2019.

[62] S. Kaewunruen, J. Sresakoolchai, W. Ma, and O. Phil-Ebosie, "Digital twin aided vulnerability assessment and risk-based maintenance planning of bridge infrastructures exposed to extreme conditions," *Sustainability*, vol. 13, no. 4, p. 2051, Feb. 2021.

[63] H. Sofia, E. Anas, and O. Faïz, "Mobile mapping, machine learning and digital twin for road infrastructure monitoring and maintenance: Case study of mohammed VI bridge in Morocco," in *Proc. IEEE Int. Conf. Moroccan Geomatics (Morgeo)*, May 2020, pp. 1–6.

[64] F. Xue, W. Lu, Z. Chen, and C. J. Webster, "From LiDAR point cloud towards digital twin city: Clustering city objects based on gestalt principles," *ISPRS J. Photogramm. Remote Sens.*, vol. 167, pp. 418–431, Sep. 2020.

[65] S. Shirowzhan, W. Tan, and S. M. E. Sepasgozar, "Digital twin and CyberGIS for improving connectivity and measuring the impact of infrastructure construction planning in smart cities," *ISPRS Int. J. Geo-Inf.*, vol. 9, no. 4, p. 240, Apr. 2020.

[66] G. White, A. Zink, L. Codecá, and S. Clarke, "A digital twin smart city for citizen feedback," *Cities*, vol. 110, Mar. 2021, Art. no. 103064.

[67] L. Shi, L. Xing, J. Bi, and B. Zhang, "Circular economy: A new development strategy for sustainable development in China," in *Proc. 3rd World Congr. Environ. Resour. Econ.*, Kyoto, Japan, 2006, pp. 3–7.

[68] J. Williams, "Circular cities," *Urban Stud.*, vol. 56, no. 13, pp. 2746–2762, 2019.

[69] Ellen MacArthur Foundation, SUN, and McKinsey Centre for Business and Environment. (2015). *Growth Within: A Circular Economy Vision for a Competitive Europe*. Accessed: May 2021. [Online]. Available: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/-EllenMacArthurFoundation_Growth-Within_July15.pdf

[70] *Take Action for the Sustainable Development Goals*. Accessed: Jun. 2021. [Online]. Available: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[71] S. Paiho, E. Mäki, N. Wessberg, M. Paavola, P. Tuominen, M. Antikainen, J. Heikkilä, C. A. Rozado, and N. Jung, "Towards circular cities—Conceptualizing core aspects," *Sustain. Cities Soc.*, vol. 59, Aug. 2020, Art. no. 102143.

[72] A. Damianou, C. M. Angelopoulos, and V. Katos, "An architecture for blockchain over edge-enabled IoT for smart circular cities," in *Proc. 15th Int. Conf. Distrib. Comput. Sensor Syst. (DCOSS)*, May 2019, pp. 465–472.

[73] M. R. Johnson and I. P. McCarthy, "Product recovery decisions within the context of extended producer responsibility," *J. Eng. Technol. Manage.*, vol. 34, pp. 9–28, Oct. 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0923474813000817

[74] Z. Chen and L. Huang, "Digital twin in circular economy: Remanufacturing in construction," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 588, Nov. 2020, Art. no. 032014.

[75] R. Rocca, P. Rosa, C. Sassanelli, L. Fumagalli, and S. Terzi, ''Integrating virtual reality and digital twin in circular economy practices: A laboratory application case,'' *Sustainability*, vol. 12, no. 6, p. 2286, Mar. 2020.

[76] R. Miehe, L. Waltersmann, A. Sauer, and T. Bauernhansl, ''Sustainable production and the role of digital twins–basic reflections and perspectives,'' *J. Adv. Manuf. Process.*, vol. 3, no. 2, Apr. 2021, Art. no. e10078.

[77] L. C. Tagliabue, F. R. Cecconi, S. Maltese, S. Rinaldi, A. L. C. Ciribini, and A. Flammini, ''Leveraging digital twin for sustainability assessment of an educational building,'' *Sustainability*, vol. 13, no. 2, p. 480, Jan. 2021.

[78] B. Esmaeilian, B. Wang, K. Lewis, F. Duarte, C. Ratti, and S. Behdad, ''The future of waste management in smart and sustainable cities: A review and concept paper,'' *Waste Manage.*, vol. 81, pp. 177–195, Nov. 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0956053X18305865

[79] *Open Mobility Foundation*. Accessed: Jun. 2021. [Online]. Available: https://www.openmobilityfoundation.org/

[80] *Mobility Data Specification in GitHub*. Accessed: Jun. 2021. [Online]. Available: https://github.com/openmobilityfoundation/mobility-data-specification

[81] Deutsche Telekom. *Berlin Digital Twin: Yes, Intermodal Traffic is Faster!* Accessed: Jun. 2021. [Online]. Available: https://dih.telekom.net/en/berlin-digital-twin/

[82] G. Bhatti, H. Mohan, and R. R. Singh, ''Towards the future of smart electric vehicles: Digital twin technology,'' *Renew. Sustain. Energy Rev.*, vol. 141, May 2021, Art. no. 110801. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032121000964

[83] J. Van Mierlo, M. Berecibar, M. E. Baghdadi, C. De Cauwer, M. Messagie, T. Coosemans, V. A. Jacobs, and O. Hegazy, ''Beyond the state of the art of electric vehicles: A fact-based paper of the current and prospective electric vehicle technologies,'' *World Electr. Vehicle J.*, vol. 12, no. 1, p. 20, Feb. 2021. [Online]. Available: https://www.mdpi.com/2032-6653/12/1/20

[84] Z. Wang, X. Liao, X. Zhao, K. Han, P. Tiwari, M. J. Barth, and G. Wu, ''A digital twin paradigm: Vehicle-to-cloud based advanced driver assistance systems,'' in *Proc. IEEE 91st Veh. Technol. Conf. (VTC-Spring)*, May 2020, pp. 1–6.

[85] T. Zhang, X. Liu, Z. Luo, F. Dong, and Y. Jiang, ''Time series behavior modeling with digital twin for internet of vehicles,'' *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, p. 271, Dec. 2019, doi: 10.1186/s13638-019-1589-8.

[86] O. E. Marai, T. Taleb, and J. Song, ''Roads infrastructure digital twin: A step toward smarter cities realization,'' *IEEE Netw.*, vol. 35, no. 2, pp. 136–143, Mar. 2021.

[87] *Fully Charged Show, The City With 16.000 Electric Buses and 22.000 Electric Taxis*. Accessed: Jun. 2021. [Online]. Available: https://fullycharged.show/episodes/the-city-with-16000-electric-buses-22000-electric-taxis/

[88] *LEAD H2020 Project, Digital Twins for Low Emissions Last Mile Logistics*. Accessed: Jun. 2021. [Online]. Available: https://www.leadproject.eu/

[89] *European Network of Living Labs*. Accessed: Jun. 2021. [Online]. Available: https://enoll.org/

[90] IBM. *How the Port of Rotterdam is Using IBM Digital Twin Technology to Transform Itself From the Biggest to the Smartest*. Accessed: Jun. 2021. [Online]. Available: https://www.ibm.com/blogs/internet-of-things/iot-digital-twin-rotterdam/

[91] V. Damjanovic-Behrendt, ''A digital twin-based privacy enhancement mechanism for the automotive industry,'' in *Proc. Int. Conf. Intell. Syst. (IS)*, Sep. 2018, pp. 272–279.

[92] United Nations News. *Staggering Rise in Climate Emergencies in Last 20 years, New Disaster Research Shows*. Accessed: Jun. 2021. [Online]. Available: https://news.un.org/en/story/2020/10/1075142

[93] *Human Cost of Disasters: An Overview of the Last 20 Years 2000–2019*, United Nations Office Disaster Risk Reduction, Geneva, Switzerland, Nov. 2020.

[94] C. Fan, C. Zhang, A. Yahja, and A. Mostafavi, ''Disaster city digital twin: A vision for integrating artificial and human intelligence for disaster management,'' *Int. J. Inf. Manage.*, vol. 56, Feb. 2021, Art. no. 102049.

[95] Y. Ham and J. Kim, ''Participatory sensing and digital twin city: Updating virtual city models for enhanced risk-informed decision-making,'' *J. Manage. Eng.*, vol. 36, no. 3, May 2020, Art. no. 04020005.

[96] J. Pang, Y. Huang, Z. Xie, J. Li, and Z. Cai, ''Collaborative city digital twin for the COVID-19 pandemic: A federated learning solution,'' *Tsinghua Sci. Technol.*, vol. 26, no. 5, pp. 759–771, Oct. 2021.

[97] H. Schuurmans, ''Digital twins help smart cities to become more resilient,'' Roy. HaskoningDHV, Tech. Rep. 11, 2019.

[98] *Water Industry Journal, Managing Incidents With the Digital Twin*. Accessed: Jun. 2021. [Online]. Available: https://www.waterindustryjournal.co.uk/managing-incidents-with-the-digital-twin

[99] P. C. Fuertes, F. M. Alzamora, M. H. Carot, and J. C. A. Campos, ''Building and exploiting a digital twin for the management of drinking water distribution networks,'' *Urban Water J.*, vol. 17, no. 8, pp. 704–713, Sep. 2020.

[100] L. Wan, T. Nochta, and J. Schooling, ''Developing a city-level digital twin–propositions and a case study,'' in *Proc. Int. Conf. Smart Infrastruct. Construct., Driving Data-Informed Decis.-Making (ICSIC)*. London, U.K.: ICE Publishing, 2019, pp. 187–194.

[101] U. Isikdag, ''BIM and IoT: A synopsis from GIS perspective,'' *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 40, p. 33, Oct. 2015.

[102] F. Dembski, U. Wössner, M. Letzgus, M. Ruddat, and C. Yamu, ''Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany,'' *Sustainability*, vol. 12, no. 6, p. 2307, Mar. 2020. [Online]. Available: https://www.mdpi.com/2071-1050/12/6/2307

[103] The OpenFOAM Foundation. *Free CFD Software*. Accessed: Jun. 2021. [Online]. Available: https://openfoam.org/

[104] H. Lehner and L. Dorffner, ''Digital geoTwin Vienna: Towards a digital twin city as geodata hub,'' *PFG, J. Photogramm., Remote Sens. Geoinf. Sci.*, vol. 88, pp. 63–75, Mar. 2020.

[105] G. Schrotter and C. Hürzeler, ''The digital twin of the city of Zurich for urban planning,'' *PFG, J. Photogramm., Remote Sens. Geoinf. Sci.*, vol. 88, pp. 99–112, Feb. 2020.

[106] Google. *COVID-19 Community Mobility Reports*. Accessed: May 2021. [Online]. Available: https://www.google.com/covid19/mobility/

[107] Apple. *COVID-19 Mobility Trends Reports*. Accessed: May 2021. [Online]. Available: https://covid19.apple.com/mobility

[108] D. J. Cook, G. Duncan, G. Sprint, and R. L. Fritz, ''Using smart city technology to make healthcare smarter,'' *Proc. IEEE*, vol. 106, no. 4, pp. 708–722, Apr. 2018.

[109] M. N. K. Boulos and P. Zhang, ''Digital twins: From personalised medicine to precision public health,'' *J. Pers. Med.*, vol. 11, no. 8, p. 745, Jul. 2021. [Online]. Available: https://www.mdpi.com/2075-4426/11/8/745

[110] R. Verma, ''Smart city healthcare cyber physical system: Characteristics, technologies and challenges,'' *Wireless Pers. Commun.*, pp. 1–21, Aug. 2021.

[111] Y. Liu, L. Zhang, Y. Yang, L. Zhou, L. Ren, F. Wang, R. Liu, Z. Pang, and M. J. Deen, ''A novel cloud-based framework for the elderly healthcare services using digital twin,'' *IEEE Access*, vol. 7, pp. 49088–49101, 2019.

[112] F. Laamarti, H. F. Badawi, Y. Ding, F. Arafsha, B. Hafidh, and A. E. Saddik, ''An ISO/IEEE 11073 standardized digital twin framework for health and well-being in smart cities,'' *IEEE Access*, vol. 8, pp. 105950–105961, 2020.

[113] *How NASA Mapped and Modeled Langley's Digital Twin*. Accessed: Jun. 2021. [Online]. Available: https://www.esri.com/about/newsroom/blog/nasa-langleys-digitaltwin/

[114] *Virtual Singapore Website*. Accessed: Jun. 2021. [Online]. Available: https://www.nrf.gov.sg/programmes/virtualsingapore

[115] *Singapore Underground*. Accessed: Jun. 2021. [Online]. Available: https://digitalunderground.sg/

[116] *New South Wales Digital Twin*. Accessed: Jun. 2021. [Online]. Available: https://nsw.digitaltwin.terria.io/

[117] *Digital Urban Twins (DUET) H2020 Project*. Accessed: Jun. 2021. [Online]. Available: https://www.digitalurbantwins.com/

[118] *SPHERE Project Website*. Accessed: Jun. 2021. [Online]. Available: https://sphere-project.eu/

[119] *Project Scene—Sustainable Community Energy Networks*. Accessed: Jun. 2021. [Online]. Available: https://www.projectscene.uk/

[120] *Future City Glasgow*. Accessed: Jun. 2021. [Online]. Available: https://futurecity.glasgow.gov.uk/

[121] *Rotterdam 3D*. Accessed: Jun. 2021. [Online]. Available: https://www.3drotterdam.nl

[122] *IMEC and TNO Launch Digital Twin of the City of Antwerp*. Accessed: Jun. 2021. [Online]. Available: https://www.imec-int.com/en/articles/imec-and-tno-launch-digital-twin-of-the-city-of-antwerp

[123] *Virtual Helsinki*. Accessed: Jun. 2021. [Online]. Available: https://www.virtualhelsinki.fi/

[124] *Helsinki's 3D City Models*. Accessed: Jun. 2021. [Online]. Available: https://www.hel.fi/helsinki/en/administration/-information/general/3d/3d

[125] *SmartKalasatama Project*. Accessed: Jun. 2021. [Online]. Available: https://fiksukalasatama.fi/en/

[126] *51World Creates Digital Twin of the Entire City of Shanghai*. Accessed: Jun. 2021. [Online]. Available: https://www.unrealengine.com/en-US/spotlights/51world-creates-digital-twin-of-the-entire-city-of-shanghai

[127] *Amaravati in Wikipedia*. Accessed: Jun. 2021. [Online]. Available: https://en.wikipedia.org/wiki/amaravati

[128] *Meet Boston's Digital Twin*. Accessed: Jun. 2021. [Online]. Available: https://www.esri.com/about/newsroom/blog/3d-gis-boston-digital-twin/

[129] *Buildmedia, Wellington Digital Twin*. Accessed: Jun. 2021. [Online]. Available: https://buildmedia.com/work/wellington-digital-twin

[130] *The 3DEXPERIENCE Platform, a Game Changer for Business and Innovation*. Accessed: Jun. 2021. [Online]. Available: https://www.3ds.com/3dexperience

[131] *Digital Twins, Modeling and Simulation, Microsoft Azure*. Accessed: Jun. 2021. [Online]. Available: https://azure.microsoft.com/en-us/services/digital-twins/

[132] Accessed: Jun. 2021. [Online]. Available: https://hxdr.com/

[133] *CityZenith*. Accessed: Jun. 2021. https://cityzenith.com/

[134] *51World Website*. Accessed: Jun. 2021. [Online]. Available: https://www.51hitech.com/

[135] *Ansys Twin Builder—Create and Deploy Digital Twin Models*. Accessed: Jun. 2021. [Online]. Available: https://www.ansys.com/products/systems/ansys-twin-builder

[136] *iTwin.js, A Starter Kit for Developing Web Applications for Infrastructure Digital Twins*. Accessed: Jun. 2021. [Online]. Available: https://www.itwinjs.org/

[137] *Deloitte Australia, Optimal Reality Digital Twin*. Accessed: Jun. 2021. [Online]. Available: https://www2.deloitte.com/au/en/pages/strategyoperations/solutions/optimal-reality-digital-twin.html

[138] *ArcGIS: A Foundation for Digital Twins*. Accessed: Jun. 2021. [Online]. Available: https://www.esri.com/arcgisblog/products/arcgis/aec/gis-foundation-for-digital-twins/

[139] *IES, Digital Twins for the Built Environment*. Accessed: Jun. 2021. [Online]. Available: https://www.iesve.com/digital-twins

[140] *GE Digital, Digital Twin Software*. Accessed: Jun. 2021. [Online]. Available: https://www.ge.com/digital/applications/digital-twin

[141] *Digital Twin, Siemens Global*. Accessed: Jun. 2021. [Online]. Available: https://new.siemens.com/global/en/company/stories/research-technologies/digitaltwin/digital-twin.html

[142] *Descartes Labs, Actionable Intelligence, Geodata Backed by Science*. Accessed: Jun. 2021. [Online]. Available: https://www.descarteslabs.com/company/#vision

[143] Accessed: Jun. 2021. [Online]. Available: https://www.zerogravity.fi/

[144] *General Data Protection Regulation*. Accessed: Jun. 2021. [Online]. Available: https://gdpr-info.eu/

[145] *Using Digital Twins to Integrate 5G Into Production Networks*, 5G Alliance Connected Ind. Automat. (5G-ACIA), Frankfurt, Germany Feb. 2021.

[146] H. X. Nguyen, R. Trestian, D. To, and M. Tatipamula, "Digital twin for 5G and beyond," *IEEE Commun. Mag.*, vol. 59, no. 2, pp. 10–15, Feb. 2021.

[147] L. U. Khan, W. Saad, D. Niyato, Z. Han, and C. S. Hong, "Digital-twin-enabled 6G: Vision, architectural trends, and future directions," *CoRR*, vol. abs/2102.12169, pp. 1–7, Feb. 2021. [Online]. Available: https://arxiv.org/abs/2102.12169

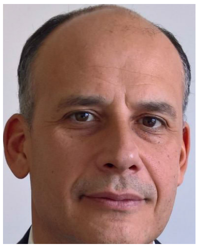
GEORGIOS MYLONAS received the M.Sc., Ph.D., and Diploma degrees from the Department of Computer Engineering and Informatics, University of Patras. He is currently the Principal Researcher with the Industrial Systems Institute, "Athena" Research and Innovation Center, Patras, Greece. Before joining Athena RC, he was a Senior Researcher at the Computer Technology Institute and Press "Diophantus." He has been involved in the AEOLUS, WISEBED, SmartSantander, OrganiCity, and E2Data EU research projects, focusing on algorithmic and software issues of sensor networks, the IoT, and smart cities. He has coauthored over 70 journal articles and conference papers. He has coordinated and was the Principal Investigator of the Green Awareness in Action (GAIA) H2020 Project, focusing on sustainability awareness and energy efficiency in the educational sector. His research interests include the areas of the IoT, smart cities, wireless sensor networks, and distributed and pervasive systems.

ATHANASIOS KALOGERAS (Senior Member, IEEE) received the Diploma degree in electrical engineering and the Ph.D. degree in electrical and computer engineering from the University of Patras, Greece. He has been with the Industrial Systems Institute, ATHENA Research and Innovation Center, since 2000, where he currently holds a position of the Research Director. He has worked as an Adjunct Faculty at the Technological Educational Foundation of Patras. He has been a Collaborating Researcher at the University of Patras, the Computer Technology Institute and Press "Diophantus," and the private sector. His research interests include cyber-physical systems, the Industrial IoT, industrial integration and interoperability, and collaborative manufacturing. Application areas include the manufacturing environment, critical infrastructure protection, smart buildings, smart cities, smart energy, and tourism and culture. He has served as a program committee member for more than 30 conferences and as a reviewer in more than 40 international journals and conferences. He has been a member of the Board of Directors of AgriFood Western Greece, since 2019. He has been a Postgraduate Scholar of the Bodossaki Foundation. He is a member of the Technical Chamber of Greece. He is a Local Editor in Greece of *ERCIM News*.

GEORGIOS KALOGERAS received the Diploma degree in electrical and computer engineering from the National Technical University of Athens, Greece. Since 2010, he has been working as a Research Associate with the Athena Research and Innovation Center, Industrial Systems Institute. He has also collaborated with the Computer Technology Institute "Diophantus" and the Patras Science Park. Over the past years, he has worked in the fields of renewable energy, energy auditing and related services, and web development. He has published a number of scientific publications and articles focused on energy performance and simulation, the smart city paradigm, and the Industrial IoT applications. His main research interests include building energy performance and simulation, the IoT applications integrated in the industrial and energy sectors, and innovative services aimed at improving area sustainability.

CHRISTOS ANAGNOSTOPOULOS received the Diploma degree in electrical and computer engineering from the University of Patras and the M.Sc. degree in integrated hardware and software systems from the Department of Computer Engineering and Informatics, University of Patras. For the last 13 years, he collaborates with the Industrial Systems Institute and the University of Patras, as a Research Fellow. He has been engaged in multiple national and European research projects. He has coauthored more than ten publications in international peer-reviewed conferences and journals. His current research interests include manufacturing systems, industrial networks, VR/AR technologies, and serious gaming.

CHRISTOS ALEXAKOS (Member, IEEE) received the D.Eng. degree in computer engineering and informatics, the M.Sc. degree in computer science and engineering, and the Ph.D. degree from the Department of Computer Engineering and Informatics, University of Patras, Greece. He was the Technical Manager of the Pattern Recognition Laboratory for ten years and the project manager in four development projects carried out by the laboratory. In 2013, he co-founded InSyBio Ltd., a bioinformatics company that delivers a cloud-based software suite for intelligent analysis of biological big data. He is currently a Research Associate with the Industrial Systems Institute, ATHENA Research and Innovation Center, Greece. He is collaborating as a Research Engineer with the Pattern Recognition Laboratory, Department of Computer Engineering and Informatics, University of Patras, and the Computer Technology Institute. He has multi-year experience in development of software applications, both web-based and standalone, including databases applications, GIS, and service-oriented applications. He is a highly experienced programmer and a software architect and has worked as a freelancer in ICT projects for both public and private sector, since 2003. He has published 15 articles in journals, 49 in conference proceedings, and five chapters in books. He also has a submitted patent to USPO. His main research interests include information systems architecture and integration in the fields of enterprise and manufacturing processes, bioinformatics, the IoT, cloud computing, and cloud manufacturing.



LUIS MUÑOZ (Senior Member, IEEE) was born in Barcelona, Spain, in 1964. He received the degree in telecommunications engineering and the Ph.D. degree from the Polytechnic University of Catalonia (UPC), Spain, in 1990 and 1995, respectively. He is currently the Head of the network planning and mobile communications with the University of Cantabria, Spain. In parallel to this activity, he serves as a consultant for the Spanish Government as well as for different companies in Europe and USA. He has participated in several national and European research projects belonging to the fourth, fifth, sixth, and seventh framework program, in which he was the Technical Manager of SmartSantander. He has published over 150 journal articles and conference papers. His research interests include advanced data transmission techniques, heterogeneous wireless multihop networks, the Internet of Things, smart cities, and applied mathematical methods for telecommunications. He has served as an Expert for the ETSI and European Commission. He has been invited to participate in the Steering Committee and Technical Program Committee of the most relevant international conferences, and serves as an editor for several journals.

• • •