A framework for incorporating smart city concepts into the management of municipal infrastructure

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Abstract

Purpose – The paper presents a smart cities (SC)-enabled infrastructure asset management (SC-IAM) framework that highlights how municipal asset managers could use emerging SC-related generations of tools to enhance the way they manage existing urban infrastructure systems and discusses its components.

Design/methodology/approach – A framework that cities can use to explicitly incorporate, smart city concepts in the monitoring and maintenance of city infrastructure assets.

Findings – The paper also highlights specific ways in which such continued infusion could enhance the city engineer's duties at the phases of monitoring and maintenance of a city's assets. The framework can help justify prospective investments and policies that city governments are contemplating currently for incorporating smart city concepts in the management of existing municipal infrastructure.

Practical implications – The paper strengthens the case for incorporating smart city concepts in municipal infrastructure management and thereby justifies prospective smart city-related investments that municipalities are contemplating currently.

Originality/value – The paper presents a novel and practical framework that cities can deploy to explicitly incorporate, smart city concepts to support their monitoring and maintenance activities for municipal infrastructure assets.

Keywords Smart cities, Infrastructure asset management, Information and communication technologies, Municipal engineering, Digital twins, Urban metaverse

Paper type Technical paper

Introduction

Study background

City infrastructure development involves the entire gamut of assessing the infrastructure need, planning, design, construction, operations, monitoring, maintenance and end of life. Of these phases, only the last three (monitoring, maintenance and end of life) are directly relevant to

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existing infrastructure and therefore are the direct responsibility of the municipal asset manager (AM). Tasks associated with these phases are often carried out in-house or through consultants and contractors hired by the ME.

In their routine work functions at these three phases, the goal of the municipal AM is to increase the capacity or quality of existing infrastructure to serve urban residents. In doing this, however, they face serious challenges in the current era, including higher demand and loading due to urban population growth, aging infrastructure, high costs and higher user expectations. These are often exacerbated by political controversies, change resistance from residents/early settlers, and the lack of right of way (Birkmann *et al.*, 2016). Other challenges include inefficient management of the existing infrastructure in many cities (World Bank, 1994). Also, there is a lack of real-time natural and anthropogenic data and immersive simulation platforms associated with infrastructure condition and usage, including user (citizen) feedback, environment–infrastructure interactions, physical condition and operational performance of city infrastructure, usage levels, user characteristics and so on.

The municipal departments of city administrations have long realized that these tasks can be facilitated not only by a core knowledge of municipal engineering and management but also by skills from other disciplines. In past decades, they have used optimization, systems simulation, and other tools in systems engineering and operations research to reach a partial resolution of these issues. However, the extant and emerging challenges impacting urban infrastructure, such as the need for real-time data integration, enhanced decision-making tools and sustainable management, have created an extensive demand for a new generation of tools. These tools include information and communication technologies (ICT), which are facilitated by a portfolio of enabling technologies, including network hardware and software, wireless networks, the internet and mobile devices. ICT elements include the Internet of Things (IoT), artificial intelligence, machine learning, blockchain, cybersecurity, augmented reality, virtual reality, digital twins, social networking and data science and analytics. It also includes novel AR- and VR-related elements of digital twins and the metaverse. In the context of urban development and in general, these technologies and their applications are pillars of the concept of smart cities (SC), a broader context where digital technology is used to collect and analyze data to enhance the development and management of urban infrastructure.

A bibliometric analysis of SC literature suggests that most SC research has focused on urban operations with relatively very little on the management of existing urban infrastructure. Mora *et al*. (2017) suggested that while the SC concept is a fast-growing research area, past literature has largely focused on the enabling technologies. It has been argued that the incorporation of SC concepts into the management of urban infrastructure by local governments and municipalities remains a challenge (Bouzguenda *et al*., 2019). Researchers have identified opportunities in the interrelationships between SC components and stakeholders (Mohammadi and Taylor, 2017b) and the relationships between industry, academia and government partners (Lombardi, 2011).

Motivation from professional infrastructure organizations

The benefits of infusing SC concepts into the various phases of infrastructure development have been recognized by professional engineering societies, infrastructure agencies and the governments of states, provinces and cities. For example, the American Society of Civil Engineers (ASCE), in its policy statement (PS 557) on smart cities, emphasized support for "integrating technology into transportation infrastructure systems in order to strengthen connectivity, workability, productivity, modal integration, and resiliency in communities" (ASCE, 2018). The underlying motivation for this policy statement was the realization that technological advancements could be leveraged as a catalyst to improve the quality of life and build and maintain successful communities from the economic, social and environmental viewpoints of sustainable development. Other policy statements of the ASCE related to smart cities and sustainability include PS-313 (Infrastructure Research and Innovations), PS-131 (Growth and Development), PS-548 (Autonomous and Connected Vehicles) and PS-454 (Intelligent Transportation Systems). The United States Department of Transportation (USDOT) describes the SC concept as a collection of digital software applications and technology in infrastructure operations and espouses their adoption to help travelers and freight move more quickly and cost-effectively (USDOT, 2015; USDOT, 2018). The Institute of Transportation Engineers (ITE) emphasizes the prospective benefits of smart community initiatives to specific population groups (Edara *et al*., 2018). Further, the SC research community has recognized that transformation to smarter management hinges on the ability of cities to understand and manage new challenges that emerge in time and space, and this is indicative of the need for timely and adequate data related to the municipal infrastructure (Mohammadi and Taylor, 2017a).

Problem statement, study objectives and study scope

In recognition of the various technological tools and applications made available by the SC-related concept of ICT, it is necessary to identify the various ways by which municipal AMs can infuse ICT in their various functions related to the monitoring, maintenance and end-of-life phases of existing municipal infrastructure. In this context, this paper identifies the opportunities presented by SC elements at these phases of existing municipal infrastructure to help the municipal AM address these challenges. For this, the paper presents a SC-enabled IAM (SC-IAM) framework.

Although the SC concept reverberates across all development sectors of a city (physical infrastructure, public health, governance, quality of life, mobility, the economy and so on), this paper focuses on infrastructure only. In addition, the paper solely focuses on the phases of monitoring and maintenance of existing assets with due recognition that the SC concept is applicable to all the phases of urban infrastructure development, from assessment of needs to end of life.

Municipal infrastructure management – elements and current challenges

Infrastructure challenges currently faced by cities

The infrastructure management processes and functions are carried out by most municipalities of major cities worldwide. Several are at the initial phase of establishing their municipal infrastructure management systems, that is, asset inventory development. However, with the increasing strain posed by growing demand, aging infrastructure and other reasons, municipal asset management has become more challenging. The United Nations projects that by 2050, over half of the global population will be residing in urban areas (UN, 2018). This is happening at a time when cities already struggle to provide the basic infrastructure required to support current populations (Birkmann *et al*., 2016). In most cities, the physical infrastructure, including the water and wastewater systems, energy infrastructure systems and transportation systems, was designed and built several decades ago to address the needs of vastly smaller populations, and the strain caused by current-day demands has begun to translate into substandard levels of service. Chee and Neo (2018) identified the challenges that cities will face in the future, and Grimm *et al*. (2008) and Alberti (2017) argued that the interactions and convergence of various changes (structural, functional and social) will engender complex problems for municipal authorities that grapple to provide critical infrastructure services for their populations. The situation in fast-growing urban areas in certain developing countries is particularly dire, as socioeconomic trends, coupled with inadequate planning or poor implementation, have exacerbated the gap between municipal infrastructure supply and demand and therefore caused the growth of slum areas (Alberti, 2017; Marx *et al*., 2013). In this vein, it is worth noting that the US National Academy of Engineering has identified as one of its 14 Grand Challenges for Engineering in the 21st century the restoration and improvement of urban infrastructure (NAE, 2018). Also, the 11th of the United Nations Sustainable Development Goals (SDGs) is “Sustainable Cities and Communities,” specifically, to make cities resilient and sustainable, among other objectives (UN, 2023).

An equally pressing challenge for infrastructure management lies in the lack of real-time data on natural and anthropogenic factors affecting infrastructure condition and usage.

Accurate, up-to-date information on environmental variables such as temperature fluctuations, precipitation and seismic activity is critical for predicting wear and damage to infrastructure systems. Similarly, data on anthropogenic influences, including traffic volumes, urban development patterns and user behavior, is critical for assessing operational performance and optimizing maintenance schedules. Without such data, municipal asset managers struggle to make timely and informed decisions, leading to delayed responses to emerging issues, inefficient resource allocation and increased maintenance costs. Furthermore, the absence of practical simulation platforms and comprehensive data integration hampers the ability of cities to model and predict the impacts of combined natural and human factors, further exacerbating the gap between infrastructure supply and demand. Addressing these data deficiencies is imperative for cities to improve resilience, optimize asset lifecycles and enhance service delivery.

Regarding funding, cities have historically relied heavily on direct subventions or subsidies from national governments for building and maintaining public infrastructure (Edwards, 2017). With rapid urbanization, cities will need to become more self-reliant and seek innovative, smart and technology-driven ways to fund, design and operate municipal infrastructure. Cities of today seek to reduce costs associated with municipal management and therefore continue to consolidate their operations by integrating functions across sectors and functional areas. Such integration could be portentous of a curse at least as much as a blessing: the growing infrastructure systems interdependencies, both spatially and functionally, lead not only to the benefits of economies of scale and economies of co-location but also to disbenefits associated with increased vulnerability to the adverse effects of any cascading perturbations that may arise. Over the past three decades, governments have become painfully aware of the profound and far-reaching consequences of such perturbations (human-caused or forces of nature) on interdependent civil infrastructure systems, such as the Northeast blackout of 2003 and Hurricane Harvey in 2017 (dubbed the costliest tropical cyclone on record at 125 bn US dollars). Evidence from the literature suggests that adequate application of ICT in infrastructure management could help reduce costs and facilitate the integration of the various sectors and functional areas of municipal infrastructure (particularly regarding asset risk management and resilience planning) and therefore mitigate the impact of disaster events (Cohen and Guo, 2021; Mitlin and Satterthwaite, 2014; Beştepe and Yildirim, 2022).

The promise of smart cities concepts

For over three decades, ICT in various relatively rudimentary forms compared to the current state has been infused by municipal AMs to enhance the management of city infrastructure. The potential of ICT in city systems management exploded with rapid advancements in computing memory and power, and thus, in city data management, and was thrust into the limelight of national and academic attention by Mariam Heller of the National Science Foundation. A pioneer of the SC concept, she stated in 2002 that "Information systems hold the key to the efficient planning, design, construction, operations, maintenance, and retirement of our nation's valuable civil infrastructure assets" (Heller, 2002). Over 20 years later, researchers generally agree that the unprecedented availability of large amounts of citizen-specific data in the current era has opened up new possibilities in municipal management and operations that were hitherto unimaginable (Abadia *et al*., 2022). Mohammadi and Taylor (2017) asserted many cities are implementing technological advancements in their operations toward smarter performance, and that these initiatives are driven by the staggering nature of existing problems, concerns for global sustainability and the quest for smart growth. Alberti (2017) stated that agencies need to cultivate the skills to efficiently manage data floods to form useful knowledge on urban systems. The researcher added that the emerging challenges in the urban areas can be addressed only through information-supported methods. Such integrated data-driven approaches can be realized through SC initiatives (Guo *et al*., 2019). Rani *et al*. (2021) argued that the development of the SC represents the best way to address the problems faced by cities of today. Patrão *et al.* (2020) presented ways to assess the extent to which SC potential has been realized. In their discussion, the digital twin and the metaverse are identified as SC elements of growing importance due to increasing realization of their vast potential benefits. In this regard, the novel concept of the "MetaOmniCity" (Kuru, 2024), which represents a deployment of metaverse technologies into an urban ecosystem, lays the ground for future research and practice in the SC body of knowledge.

Smart cities – the nexus with infrastructure asset management

Revisiting the question, "what is a smart city?"

According to the American Society of Civil Engineers (ASCE, 2018), the SC concept is "motivated by the need for intelligent ways to provide quick and reliable information to facilitate any phase of the life cycle development of municipal infrastructure in a manner that is economic, social, and environmentally successful." The 2018 IEEE International Smart Cities Conference, in articulating its conference theme, stated that, "as sensors, data, connectivity, networks, and analytics offer opportunities to improve each of these systems independently, the common elements of technology infrastructure offer more opportunities for interoperability across systems and to reframe how we optimize and make decisions about these systems." The potential of SC in infrastructure asset management has been duly recognized by researchers including Caragliu *et al.* (2011), Albino *et al.* (2015), Mohanty *et al.* (2016), Derrible (2016), Eiza *et al.* (2020) and Rani *et al.* (2021). In the specific context of infrastructure, one of the most impactful emerging technologies that enable the SC concept is the digital twin, which is a dynamic virtual model of an object or system that mirrors its lifecycle and behavior. Continuously updated with real-time data, digital twins leverage simulation, machine learning and analytical reasoning to support informed decision-making. Researchers have recognized the need for municipal AMs to identify and measure the interactions among the trio of human, infrastructure and technology in a city (Nam and Pardo, 2011) and others have discussed the subject in some detail (Deren *et al.*, 2021; Haluskova, 2023). Mohammadi and Taylor (2017) introduced an innovative smart city digital twin paradigm where spatiotemporal fluctuations of these interactions can be integrated into a real-time analytics platform. The benefits of such a platform can be immense, as municipal AMs are provided unparalleled opportunities to exchange (and learn from) spatiotemporal information with the city. With Mohammadi and Taylor's (2017) innovation, it is possible to update the digital twin with new data and equipped with machine learning. That way, it can become more intelligent with time, providing the municipal AM with both anticipatory and retrospective insights into the municipal infrastructure performance and associated factors. The SC concept continues to grow in terms of its elements and what it can achieve. Recently, Kuru (2024) proposed the "MetaOmniCity," as a natural extension of SC digital twins to show how metaverse technologies could be implemented in an urban ecosystem. It is expected that in MetaOmniCity, the municipal AM can experience the existing or prospective operational conditions in response to the ME's prospective investments, policies or actions to enhance the city infrastructure through shared and immersive 3D spaces where the real and virtual worlds can be connected and interact in real time (Kuru and Kuru, 2024). Also, it is anticipated that MetaOmniCity will provide the municipal AM with valuable insights into the effect of prospective municipal interventions by offering a resident-centric urban metaverse platform for immersive experiences. As such, in general, the integration of smart cities digital twins and the metaverse can help cities to provide their infrastructure-related municipal services more efficiently. Jacques *et al.* (2014) presented insightful perspectives of integrated technological solutions in urban environments to highlight the link between SC and innovative urban management.

Infrastructure-related outcomes of smart cities

The goals of municipal agencies are generally consistent with the benefits or outcomes sought by SC initiatives (Halfawy, 2008; Caraglui *et al.*, 2019). The nexus between SC and municipal infrastructure management seems to be characterized by the directness of their relationship because investments in smart cities are essentially investments related to municipal infrastructure, and such investments are currently being approved, planned, designed and operated by the city engineer's office responsible for municipal management. However, there also exist indirect reverberative effects, which we discuss subsequently in this paper.

The outcomes of SC initiatives, particularly in terms of the sustainability pillars (Hall, 2000; Haughton and Hunter, 2004; Addas, 2023), are of great interest to stakeholders (Berglund *et al.*, 2020), including infrastructure-related institutions such as the American Public Works Association (APWA) (2013) and the American Society of Civil Engineers (ASCE) (APWA, 2013; ASCE, 2010). It has been shown that the application of SC concepts can help deliver more sustainable outcomes of infrastructure asset management in urban areas (Mitlin and Satterthwaite, 2014; Balaji and Soori, 2019; Cohen and Guo, 2021). SC technologies enable accounting for city residents' consumption patterns, promoting renewable energy use (O'Dwyer *et al.*, 2019), facilitating pollution prevention and waste management, including reuse and recycling and efficient disposal (Pereira *et al.*, 2019) and improving energy management in a city (Liu *et al.*, 2019; Mohammadi *et al.*, 2017). Additionally, in a smart city, residents' participatory action, engagement and prudent resource management and investments in physical and cyber infrastructure, significantly lead to enhanced quality of life for all the city residents (Caragliu *et al.*, 2019; Addas, 2023; Kuru and Kuru, 2024). From an infrastructure management perspective, this is a critical consideration because, through enhanced communication, city residents can receive precise and contextualized information in real time regarding infrastructure-related services to the residents. Also in the literature, the governance perspective has been addressed, as SC concepts can help improve government efficiency and effectiveness and enable the city residents and relevant entities to gain quick access to official documents. This will help facilitate efficient public services, monitor and manage situations that impact public safety and help the city authorities respond effectively and quickly to emergency infrastructure-related situations (Uddin, 2019). In a specific application that demonstrated the efficacy of SC concepts, Ning *et al.* (2019) showed how the municipality's response time to information reported by the infrastructure user could be minimized.

Opportunities for SC concepts at each phase of city infrastructure development

A clear definition of the various phases of the infrastructure life cycle and the elements of a typical asset management process is useful to serve as a basis upon which SC concepts can be incorporated in infrastructure asset management (IAM). In this paper, we focus on the phases of infrastructure monitoring and maintenance, as those are the phases most related to municipal infrastructure asset management. Notably, infrastructure managers primarily oversee these phases, which involve not only assessing the infrastructure's impacts on the environment and vice versa but also determining the optimal timing and scope of maintenance activities. These include preventive, corrective, and rehabilitation measures to ensure sustained infrastructure performance and resilience.

At each phase, municipal AMs undertake tasks that include analysis, evaluation and selection of optimal alternatives at that phase. For describing physical structures or operational processes, they use analytical or numerical models and tools; and for evaluation, they typically use decision-support tools, including life-cycle costing, multiple criteria analysis and optimization. The following discussion explores how municipal AMs can integrate SC concepts into the monitoring and maintenance phases, as these are the most pertinent and impactful stages for municipal infrastructure management.

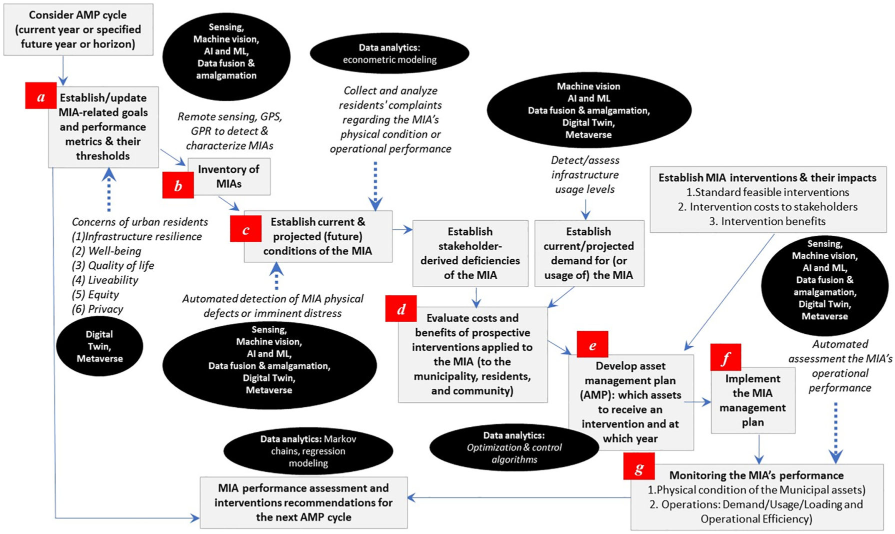
At the monitoring phase, information technology could be used to facilitate not only the city residents' reporting of defective or hazardous situations on the city infrastructure network but also the collation of such information through heat maps and reporting such summary information to the city or town residents. In the maintenance phase, tasks include assessing financial feasibility and making critical decisions, as pointed out by Shahfahad *et al.* (2022). These decisions often incorporate residents' concerns about the environmental, economic and social impacts of maintenance activities, such as the location, design and duration of work zones. Failing to address these concerns can harm the public relations image of the municipal department, underscoring the need for inclusive and well-communicated maintenance planning. Information technologies, including websites, cell phone apps and dedicated online chat rooms, can provide confidential and convenient platforms for city residents; feedback (Wang *et al.*, 2019), financial monitoring (Kupko *et al.*, 2019) and utilities planning (Ai *et al.*, 2019). Maintenance considerations related to smart cities and sustainability include the use of novel materials that are associated with greater longevity and superior performance (Kim, 2019; Amirkhanian, 2019) or minimal adverse impacts on energy use (Mohammadi *et al.*, 2017; O'Dwyer *et al.*, 2019), hydrologic patterns (Avishreshth and Prapoorna, 2019) and emissions (Jan, 2019; Novieto *et al.*, 2023). Other SC-related sustainability considerations for existing infrastructure repair or renewal are discussed at length by Aboneama (2020), Kamal (2015) and Momade *et al.* (2021). The maintenance and monitoring phases involve the efficient use of funds, time, manpower, materials and equipment to assess and track urban infrastructure damage from the natural environment and degradation of the natural environment due to urban infrastructure maintenance. Also at the maintenance phase, opportunities exist for long-lasting or self-healing materials and efficient use of materials (Ahmed, 2017; Chang, 2019; Abdullah and Usman, 2022) to enhance economic sustainability and minimal adverse impact on surface waters and soils and air quality.

In addition, the maintenance, monitoring and end-of-life phases offer great potential to infuse SC and sustainability concepts (Pereira *et al.*, 2019; Anagnostopoulos, 2017; Ong and Hwang, 2019). City engineers leverage ICT and analytical tools to facilitate safe, efficient and sustainable operations of their infrastructure and to improve the quality of life for all the city residents (Mansour *et al.*, 2022). The inspection/monitoring phase involves tracking of infrastructure condition and operational performance, forecasting and monitoring of infrastructure demand/usage for various infrastructure classes (Marsal-Llacuna *et al.*, 2014) and automated detection of defects (Choi and Do, 2019). This phase also involves monitoring natural disasters and anthropogenic threats to the city infrastructure (Alyousef *et al.*, 2015) and modeling climate-related impacts (including thermal comfort) to the city's residents (Mallick *et al.*, 2013; Shahfahad *et al.*, 2022). Nairne Schamne *et al.* (2022) discussed how building information modeling and sustainability assessment could be applied to enhance the intelligent management of buildings in a city. Lighting infrastructure fitted with cameras and video could help the AM in monitoring other city infrastructure, thus increasing the safety and security of the general public (Patrão *et al.*, 2020), assessing infrastructure physical conditions and reducing energy consumption, pollution and emissions (Mohammadi *et al.*, 2017; O'Dwyer *et al.*, 2019; Locke, 2022). Magee *et al.* (2019) discussed how intelligent remote sensing could be used to realize smart management of infrastructure assets, and Kuru (2024) and Kuru and Kuru (2024) discussed the creation of an urban metaverse and digital twin that provides an immersive platform that could play various AM roles, including *ex ante* and *ex poste* assessments of infrastructure investments prospectively and retrospectively, respectively. Such platforms will be useful not only for quick and effective monitoring of existing or prospective urban conditions but also for assessing the impacts of prospective actions by the municipal AM regarding infrastructure maintenance and possibly, end-of-life options.

A framework for incorporating SC concepts into municipal infrastructure management

Components of the proposed framework

The suggested architecture for municipal infrastructure asset management (IAM) in the context of a smart city (Figure 1) is largely consistent with the basic principles of asset management espoused by agencies and institutions associated with infrastructure asset management (AASHTO, 2011; Woodhouse, 2015). In the proposed process, the city (a)



Note(s): Key stakeholders are the municipality (agency), city residents, & the community
MIA-Municipal Infrastructure Asset
AMP-Asset Management Program
Source(s): Authors' own work

Figure 1. Smart-cities enabled infrastructure asset management (SC-IAM) framework showing opportunities for incorporating SC elements (black ovals)

establishes its performance goals and expectations, (b) updates the inventory (record) of all its municipal infrastructure assets (MIA) and (c) establishes current and projected conditions of the infrastructure assets. Next, the city identifies the extant physical infrastructure defects (e.g. cracking, spalling and corrosion), measures their severity and spread and identifies the alternative repairs. The municipal AM can use the infrastructure deterioration models to address questions regarding the current condition of their infrastructure assets, condition forecasting for each infrastructure at any future year and quantify the impacts of infrastructure deterioration factors. Then, (d), the AM assesses not only the effectiveness of the alternative prospective interventions but also the costs they incur to each stakeholder (the municipal department, the infrastructure users and the city residents and community). The urban metaverse and digital twin concept (Kuru, 2024) can facilitate the acquisition of city resident feedback regarding these functions. In (e), the city then develops a long-term asset management workplan for the municipal infrastructure repair and renewal. Often, funding for such repairs is not only insufficient to meet the overall financial need but also subject to economic conditions and therefore is characterized by uncertainty. Therefore, any assessment of the financial need must also be accompanied by a candid assessment of the efficacy of current and prospective revenue streams to meet the financial need. It is also beneficial to assess the tradeoffs between prospective spending levels and the resulting levels of infrastructure condition and operational performance. The municipal AM presents such tradeoff information to legislators or city councils to support their requests for funding the recommendations from the asset management plan.

Next (f), the city implements the developed asset management work program through its contracts division (often for major rehabilitation interventions) and its in-house maintenance division (for relatively minor or routine preservation work). In (g), ex post evaluation and monitoring of performance outcomes and feedback to (and from) decision-makers and the city residents (Bouzguenda *et al*., 2019; White *et al*., 2021) is carried out. This is a critical but often overlooked aspect of municipal infrastructure management. To help address this aspect of infrastructure management, the adoption of the urban metaverse and digital twin concepts (Kuru, 2024) can serve as valuable tools for the municipal agency in assessing the efficacy of completed investments and established policies. This approach can enhance the city's position regarding fiduciary stewardship of the public infrastructure and facilitate interactive conversations with the city residents and infrastructure users regarding the impact of their tax dollars or user fees (or inadequacies thereof) on the infrastructure system's longevity.

To carry out these functions, there exist traditional tools that are used and prospective (SC-related tools) that could be used. The traditional tools include statistical modeling, data mining, economic and financial analysis, numerical simulation and optimization. For example, due to the typical large size of infrastructure inventory at most municipalities coupled with the multiplicity of decision criteria, advanced tools are needed to identify globally optimal solutions within reasonable computational times. The analytical tools also help the municipality to estimate or predict investment outcomes associated with the agency (investment spending), the infrastructure user and community (downtime-related durations and costs) and the benefits of investment-inducing enhancements in the infrastructure's physical condition or life extension. These tools also help the municipality assess the tradeoffs between infrastructure spending and performance. The smart cities-related tools are those marked in black circles in the figures and have been discussed in this paper.

Discussion

This paper focuses on the role of municipal AM managers and how their functions could be enhanced through the adoption of specific SC elements. Presents. It introduces a framework to help infrastructure managers explicitly identify and integrate SC elements into routine tasks such as infrastructure monitoring, repair decision-making and feedback collection. In this section, we present a discussion of broader issues that will influence or be influenced by the application of the framework.

The emergence of the urban metaverse

As a tool, simulation has always been a valuable recourse for studying various scenarios of a system prior to field implementation because full-scale real-life applications are typically impractical, expensive and, in some cases, even unethical. Digital twins and metaverse technologies (Kuru, 2024) present a unique opportunity to create a bridge between virtual and real worlds, providing a platform to carry out unlimited scenarios of infrastructure configurations, settings, designs, usage patterns and environmental interactions. Existing literature suggests that IoT-supported smart city digital twin paradigms have been developed to facilitate superior characterizations of the human-infrastructure-technology nexus and associated spatiotemporal fluctuations within a city (Mohammadi and Taylor, 2017), and similar initiatives have been highlighted recently (Haluskova, 2023). In practice, digital twin and related technology have been recognized as a key strategic technology trend in various cities in the current decade and have been recognized by public organizations as an effective tool for city planning and management (PWC, 2022). Moreover, with advancements in machine learning and AI, the frontiers of digital twin applications in systems simulation and analysis continue to expand (Xu *et al*., 2024). A recent prescient study (Kuru, 2024) acknowledged the role of the COVID pandemic in highlighting the importance of a city's virtual scale model (i.e. its digital twin, which evolves over time and space and incorporates automated services that ultimately enhance urban residents' quality of life). These researchers invariably point to a science fiction-like emerging future where data-driven SC with digital twins is transformed (via reconstruction of high-fidelity virtual worlds that interact with the real world) into cities of virtual habitation that provide an opportunity for shared urban experiences that can provide vital feedback to the municipal asset manager (Mohammadi and Taylor, 2017; Xu *et al.*, 2024; Kuru, 2024; Kuru and Kuru, 2024). In this regard, Kuru (2024) described a prospective and novel SC ecosystem that can provide users with high-quality immersive experiences and an urban metaverse ecosystem framework (termed "MetaOmniCity" by the researcher). The wider benefits of this innovation include the invaluable acquisition of insights (of city infrastructure operating conditions) by both the municipal AM and the infrastructure users (city residents) and thus, the making of more informed design and policy directions by the municipal AM and city planners.

Recognition of the role of ICT's ever-increasing capabilities

The field of SC is fast growing as it is tied strongly to the field of ICT. With its continuing explosion in computing power and memory storage capabilities coupled with the rise of AI and machine learning, the field of ICT continues to propel to unprecedented heights, with ever-expanding realms of what it can achieve. This trend is expected to not only continue in pace, offering unparalleled opportunities to collect and store vast amounts of data to facilitate complex analysis and visualizations associated with engineering systems and associated information on citizen's feedback, usage levels, system performance, materials deterioration and system-environment-citizen interactions (Marjani *et al.*, 2017; Mohammadi and Taylor, 2017). From the perspective of infrastructure systems management, these developments translate into enhanced capabilities for characterizing existing or preferred conditions (thresholds) toward more reliable and effective decision-making. This is consistent with the long-held realization that ICT advancements can be leveraged to acquire efficiencies in the way city infrastructures are planned, constructed, operated, maintained and monitored (Kourtit and Nijkamp, 2012; Sousa *et al.*, 2021). ICT has brought several benefits in terms of infrastructure data availability and networked platforms for immersive experiences, including metaverse platforms and urban digital twins. Meanwhile, some far-sighted researchers, including Kuru and Kuru (2024), have aptly recognized that the virtues of technologies like data availability and the IoT, paradoxically could also open up serious threats in terms of data privacy and security, thereby potentially jeopardizing the efficacy of urban metaverse cyberspaces with urban twins.

Reverberative effects

Application of the proposed framework could lead to increased reliability of infrastructure monitoring and usage levels, capability for timely and proactive repairs, and ultimately, enhanced infrastructure condition, longevity and resilience. However, infrastructure is only one of the several application areas or sectors that could benefit from SC concepts. As discussed widely in the literature, SC concepts are also applicable to other sectors of municipal administration. For example, facilities and systems associated with public health and transportation, with accompanying impacts related to energy use, citizen safety and security, mobility of people and goods, accessibility to social centers, quality of life and livability and inclusivity (Albino *et al.*, 2015; Edara *et al.*, 2018; Bouzguenda *et al.*, 2019; Makkonen and Inkinen, 2024). Therefore, prospective enhancements in infrastructure management occasioned by the implementation of the proposed framework could reverberate not only at other phases of infrastructure management (planning, design, construction and operations) but also at other sectors as well (commerce, healthcare, social service and education).

Concluding remarks

Summary

The framework developed in this paper can help municipal AMs identify relevant SC elements and incorporate them in the management of municipal infrastructure. In recognition of the challenges associated with current-day infrastructure management, the paper identifies opportunities to infuse SC concepts into the monitoring and maintenance of urban infrastructure.

The paper reviews the concept and elements of SC as a basis for identifying their potential roles in addressing these challenges and presents a framework that cities can use explicitly to incorporate SC concepts in the management of their municipal infrastructure assets. It is anticipated that the proposed framework can be used as a basis for requests for increased funding for SC investments in the management of existing infrastructure in cities. That way, the AM's decisions can help ensure sustainability-related objectives of minimal damage to (and maximum benefits from) the external environment (social, economic and ecology) and maximum resistance and recovery from external agents of deterioration or destruction. The emergence of novel SC concepts, in particular, digital twins and metaverse technologies, offers unparalleled opportunities for immersive experiences for the municipal AM and the city residents to better characterize and comprehend the consequences of alternative actions or policies regarding the existing infrastructure.

Suggested directions for future research

The current paper has a narrow scope, by design, as it addresses a relatively unchartered application area of the SC concept. First, it addresses only the infrastructure element of SC. Secondly, it focuses on only the maintenance and monitoring phases of urban infrastructure systems. Future work could address how SC concepts could help address other sectors of urban development (governance, public heath, energy, education, etc.) and, regarding the infrastructure sector, also enhance other phases of infrastructure development (planning, design, construction and operations).

Secondly, there exists a plethora of current research efforts in the SC domain, and the concept continues to attract a great deal of attention from a wide variety of disciplines, including infrastructure management, transportation modeling and simulation, urban planning, energy management and governance and political science. Across these disciplines, it is often useful to classify SC research areas into several categories: the enabling technologies (or the fundamental elements), policy and planning, human factors, infrastructure development and deployment. Regarding the enabling technologies, active research areas include the role of 5G, physical and cyber infrastructures for SC, urban metaverse technologies and digital twins, urban data analytics and management and online platforms to facilitate the participation of city residents and organizations in infrastructure monitoring and municipal governance. Policy and planning research could include consumer or agency demand for various elements or component systems of SC, and additional inquiry regarding the beneficial and adverse effects associated with SC concepts facilitates the management of municipal infrastructure, including residents' privacy and data security. Also, computer and real-life simulations of systems and subsystems related to SC, such as autonomous vehicles, through metaverse platforms, could help throw more light on related human factors as well as the overall societal benefits and disbenefits associated with these subsystems. Another possible area of future research is to estimate the work scope and funding needs associated with preparing the current physical or cyber infrastructure at cities to adequately accommodate various prospective SC components and subsystems, including connected and autonomous vehicles. Finally, future research could explore further the newest technologies that further expand the capabilities of urban metaverse platforms and their efficacy in terms of simulation reliability, human factors and cybersecurity.

References

AASHTO (2011), *Transportation Asset Management Guide: A Focus on Implementation*, 1st ed., AASHTO, Washington, DC.

Abadía, J.J.P., Walther, C., Osman, A. and Smarsly, K. (2022), "A systematic survey of Internet of Things frameworks for smart city applications", *Sustainable Cities and Society*, Vol. 83, 103949, doi: 10.1016/j.scs.2022.103949.

Abdullah, K. and Usman, A.M. (2022), "Development of comprehensive carbon footprint and environmental impact indicators for building transportation assessment", *Frontiers in Engineering and Built Environment*, Vol. 2 No. 3, pp. 167-183, doi: 10.1108/febe-11-2021-0053.

Aboneama, D.W. (2020), "Applying sustainable principles to create new urban areas and developing existing cities in 2030 vision of Saudi Arabia", in *Springer_ASTI Resilient and Responsible Smart Cities Book*, Vol. 1.

Addas, A. (2023), "The concept of smart cities: a sustainability aspect for future urban development based on different cities", *Frontiers in Environmental Science*, Vol. 11, 1241593, doi: 10.3389/fenvs.2023.1241593.

Ahmed, F.H. (2017), "Improving construction materials management practices in construction sites", Doctoral dissertation, Tun Hussein Onn University, Malaysia.

Ai, C., Qiu, S., Xue, B. and Chen, Y. (2019), "Smart cities powered by smart utility planning", *International Conference on Transportation and Development 2019 – Engineering Smart Mobility for the Smart City*, Alexandria, VA, June 9–12, 2019.

Alberti, M. (2017), "Grand challenges in urban science", *Frontiers in Built Environment*, Vol. 3, p. 6, doi: 10.3389/fbuil.2017.00006.

Albino, V., Berardi, U. and Dangelico, R.M. (2015), "Smart cities: definitions, dimensions, performance, and initiatives", *Journal of Urban Technology*, Vol. 22 No. 1, pp. 3-21, doi: 10.1080/10630732.2014.942092.

Alyousef, K., Al-Amri, A., Fnais, M., Abdelrahman, K. and Loni, O. (2015), "Site effect evaluation for Yanbu City urban expansion zones, western Saudi Arabia, using microtremor analysis", *Arabian Journal of Geosciences*, Vol. 8 No. 3, pp. 1717-1729, doi: 10.1007/s12517-014-1310-5.

Amirkhanian, S. (2019), "Developments in civil engineering smart infrastructure materials", *2019 International Conference on Smart Cities, Keynote Address*, Seoul, Korea, July 16–20.

Anagnostopoulos, T., Zaslavsky, A., Kolomvatsos, K., Medvedev, A., Amirian, P., Morley, J. and Hadjieftymiades, S. (2017), "Challenges and opportunities of waste management in IoT-enabled smart cities: a survey", *IEEE Transactions on Sustainable Computing*, Vol. 2 No. 3, pp. 275-289, doi: 10.1109/tsusc.2017.2691049.

APWA (2013), *Principles of Sustainability*, APWA Center for Sustainability, Washington, DC.

ASCE (2010), *Policy Statement 418 – the Role of the Civil Engineer in Sustainable Development*, ASCE, Reston, VA.

ASCE (2018), *Policy Statement 557-Smart Cities*, The American Soc. of Civil Eng., Reston, VA.

Avishreshth, P. and Prapoorna, K. (2019), "Smart city initiatives: pervious concrete shoulders and berms", *2019 International Conference on Smart Cities*, Seoul, Korea, July 16–20.

Balaji, A.K. and Soori, P.K. (2019), "Sustainable transportation infrastructure for smart cities in the Gulf Cooperation Council: the case of electric vehicle charging", in *Smart Cities in the Gulf*, Palgrave Macmillan, Singapore, pp. 107-121.

Berglund, E.Z., Monroe, J.G., Ahmed, I., Noghabaei, M., Do, J., Pesantez, J.E., Levis, J., Bardaka, E., Han, K. and Proestos, G.T. (2020), "Smart infrastructure: a vision for the role of the civil engineering profession in smart cities", *Journal of Infrastructure Systems*, Vol. 26 No. 2, 03120001, doi: 10.1061/(asce)is.1943-555x.0000549.

Beştepe, F. and Yildirim, S.Ö. (2022), "Acceptance of IoT-based and sustainability-oriented smart city services: a mixed methods study", *Sustainable Cities and Society*, Vol. 80, 103794, doi: 10.1016/j.scs.2022.103794.

Birkmann, J., Welle, T., Solecki, W., Lawsa, S. and Matthias, G. (2016), "Boost resilience of small and mid-sized cities, smaller settlements are growing faster than megacities", *Nature*, Vol. 537 No. 7622, pp. 605-608, doi: 10.1038/537605a.

Bouzguenda, I., Alalouch, C. and Fava, N. (2019), "Towards smart sustainable cities: a review of the role digital citizen participation could play in advancing social sustainability", *Sustainable Cities and Society*, Vol. 50, 101627, doi: 10.1016/j.scs.2019.101627.

Caragliu, A. and Del Bo, C.F. (2019), "Smart innovative cities: the impact of smart city policies on urban innovation", *Technological Forecasting and Social Change*, Vol. 142, pp. 373-383, doi: 10.1016/j.techfore.2018.07.022.

Caragliu, A., Del Bo, C. and Nijkamp, P. (2011), "Smart cities in Europe", *Journal of Urban Technology*, Vol. 18 No. 2, pp. 65-82, doi: 10.1080/10630732.2011.601117.

Chang, C.M. (2019), "Asset management systems for a sustainable development of smart cities", *2019 International Conference on Smart Cities*, Seoul, Korea, July 16–20.

Chee, C.-H. and Neo, H. (2018), "The 5 biggest challenges cities will face in the future", available at: www.weforum.org/agenda/2018/10/the-5-biggest-challenges-cities-will-face-in-the-future/

Choi, S. and Do, M. (2019), "Vision-based automated crack detection for bridge inspection using unmanned aerial vehicles", *2019 International Conference on Smart Cities*, Seoul, Korea.

Cohen, S. and Guo, D. (2021), *The Sustainable City*, Columbia University Press, New York.

Deren, L., Wenbo, Y. and Zhenfeng, S. (2021), "Smart city based on digital twins", *Computational Urban Science*, Vol. 1, p. 4, doi: 10.1007/s43762-021-00005-y.

Derrible, S. (2016), "Complexity in future cities: the rise of networked infrastructure", *International Journal of Urban Sciences*, Vol. 21 No. 1, pp. 68-86, doi: 10.1080/12265934.2016.1233075.

Edara, P., Kupko, J., Lavrenz, S., Lee, S. and Puionke, C. (2018), "Harnessing the 'smart cities' initiative to improve mobility for aging and disadvantaged populations", *Leight's Lite Lights*, available at: https://www.ite.org/pub/?id=D45ABC10-B736-4D42-40CB-CE6812B42D6A

Edwards, C. (2017), "Infrastructure investment", in *Cato Handbook for Policymakers*, 8th ed., Cato Institute, Washington, DC.

Eiza, M.H., Cao, Y. and Xu, L. (2020), *Toward Sustainable and Economic Smart Mobility: Shaping the Future of Smart Cities*, Eds., World Scientific, Singapore.

Grimm, N.B., Foster, D., Groffman, P., Grove, J.M., Hopkinson, C., Nadelhoffer, K.J., Pataki, D.E. and Peters, D.P. (2008), "The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients", *Frontiers in Ecology and the Environment*, Vol. 6 No. 5, pp. 264-272, doi: 10.1890/070147.

Guo, Y.-M., Huang, Z.-L., Guo, J., Li, H., Guo, X.-R. and Nkeli, M.J. (2019), "Bibliometric analysis on smart cities research", *Sustainability*, Vol. 11 No. 13, p. 3606, doi: 10.3390/su11133606.

Halfawy, M. (2008), "Integration of municipal infrastructure asset management processes: challenges and solutions", *Journal of Computing in Civil Engineering*, Vol. 22 No. 3, pp. 216-229, doi: 10.1061/(asce)0887-3801(2008)22:3(216).

Hall, R.E. (2000), "The vision of a smart city", *Proceedings of the 2nd International Life Extension Technology Workshop*, Paris, France.

Haluskova, B. (2023), "Digital twin in smart city", *Transportation Research Procedia*, Vol. 74, pp. 1471-1478, doi: 10.1016/j.trpro.2023.11.308.

Haughton, G. and Hunter, C. (2004), *Sustainable Cities*, Routledge, Abingdon.

Heller, M. (2002), "Independencies in civil infrastructure systems", *7th Annual Symposium on Frontiers of Engineering, National Academy of Engineering*, National Academies Press.

Jacques, E., Neuenfeldt Júnior, A., De Paris, S., Francescatto, M. and Siluk, J. (2014), "Smart cities and innovative urban management", *Heliyon*, Vol. 10 No. 6, e27850, doi: 10.1016/j.heliyon.2024.e27850.

Jan, S.H. (2019), "Smart transport roads designed by nanocomposite coating of polyurethane and carbon nanotubes", *2019 International Conference on Smart Cities*, Seoul, Korea, July 16-20.

Kamal, M.A. (2015), "Climatic control and energy conservation through landscape design", *International Journal of Landscape Planning and Architecture*, Vol. 1 No. 2, pp. 10-17.

Kim, B. (2019), "Super concrete technology opening a new way of smart infrastructures", *Keynote Address, 2019 International Conference on Smart Cities*, Seoul, Korea, July 16–20.

Kourtit, K. and Nijkamp, P. (2012), "Smart cities in the innovation age", *Innovation: The European Journal of Social Science Research*, Vol. 25 No. 2, pp. 93-95, doi: 10.1080/13511610.2012.660331.

Kupko, J.J. and Ptoe, M. (2019), “Smart Columbus: a mobility ecosystem”, *ITE Journal*, Vol. 89 No. 8, p. 18.

Kuru, K. (2024), “MetaOmniCity: toward immersive urban metaverse cyberspaces using smart city digital twins”, *IEEE Access*, No. 99, p. 1.

Kuru, K. and Kuru, K. (2024), “Urban metaverse cybercommunities and blockchain based privacy-preserving deep learning authentication and verification with immersive metaverse devices”, *IEEE Sixth International Conference on Blockchain Computing and Applications (BCCA 2024)*, Dubai, UAE, 26–29 November 2024.

Liu, Y., Yang, C., Jiang, L., Xie, S. and Zhang, Y. (2019), “Intelligent edge computing for IoT-based energy management in smart cities”, *IEEE Network*, Vol. 33 No. 2, pp. 111-117, doi: 10.1109/mnet.2019.1800254.

Locke, J. (2022), “Top 12 smart cities in the U.S. – smart cities examples”, available at: https://www.digi.com/blog/post/smart-cities-in-the-us-examples

Lombardi, P. (2011), “New challenges in the evaluation of smart cities”, *Network Industries Quarterly*, Vol. 13 No. 3, pp. 8-10.

Magee, B., Hamill, M. and Millar, P. (2019), “Development of an intelligent remote sensing technique as a tool for smart infrastructure asset management”, in *Proceedings of the International Conference on Smart Cities (ICSC-2019)*, pp. 1-7.

Makkonen, T. and Inkinen, T. (2024), “Inclusive smart cities? Technology-driven urban development and disabilities”, *Cities*, Vol. 154, 105334, doi: 10.1016/j.cities.2024.105334.

Mallick, J., Rahman, A. and Singh, C.K. (2013), “Modeling urban heat islands in heterogeneous land surface and its correlation with impervious surface area by using night-time ASTER satellite data in highly urbanizing city”, *Advances in Space Research*, Vol. 52 No. 4, pp. 639-655, doi: 10.1016/j.asr.2013.04.025.

Mansour, M., Alsulamy, S., Alghamdi, S. and Qureshi, M.R. (2022), “Assessing the risk of university-student driving to enhance safe and sustainable traffic management: a logistic regression and analytic hierarchy approach”, *Technical Gazette*, Vol. 29 No. 2, pp. 692-701.

Marjani, M., Nasaruddin, F., Gani, A., Karim, A., Hashem, I.A.T., Siddiqa, A. and Yaqoob, I. (2017), “Big IoT data analytics: architecture, opportunities, and open research challenges”, *IEEE Access*, Vol. 5, pp. 5247-5261.

Marsal-Llacuna, M.L., Colomer-Llinas, J. and Melendez-Frigola, J. (2014), “Lessons in urban monitoring taken from sustainable and livable cities to better address the smart cities initiative”, *Technological Forecasting and Social Change*, Vol. 90 B, pp. 611-622, doi: 10.1016/j.techfore.2014.01.012.

Marx, B., Stoker, T. and Suri, T. (2013), “The economics of slums in the developing world”, *Journal of Economic Perspectives*, Vol. 27 No. 4, pp. 187-210, doi: 10.1257/jep.27.4.187.

Mitlin, D. and Satterthwaite, D. (2014), “Sustainable development and cities”, in *Sustainability the Environment and Urbanization*, Routledge.

Mohammadi, N. and Taylor, J.E. (2017a), “Smart city digital twins”, *2017 IEEE Symposium Series on Computational Intelligence (SSCI)*, Honolulu, HI, USA, pp. 1-5, doi: 10.1109/ssci.2017.8285439.

Mohammadi, N. and Taylor, J.E. (2017b), “Urban infrastructure-mobility energy flux”, *Energy*, Vol. 140, pp. 716-728, doi: 10.1016/j.energy.2017.05.189.

Mohammadi, N., Taylor, J.E. and Wang, Y. (2017), “Towards smarter cities: linking human mobility and energy use fluctuations across building types”, *50th Hawaii International Conference on System Sciences-HICSS 50*, pp. 2824-2833.

Mohanty, S.P., Choppali, U. and Kougianos, E. (2016), “Everything you wanted to know about smart cities: the Internet of Things is the backbone”, *IEEE Consumer Electronics*, Vol. 5 No. 3, pp. 60-70, doi: 10.1109/mce.2016.2556879.

Momade, M.H., Durdyev, S., Estrella, D. and Ismail, S. (2021), “Systematic review of application of artificial intelligence tools in architectural, engineering and construction”, *Frontiers in Engineering and Built Environment*, Vol. 1 No. 2, pp. 203-216, doi: 10.1108/febe-07-2021-0036.

Mora, L., Bolici, R. and Deakin, M. (2017), "The first two decades of smart-city research: a bibliometric analysis", *Journal of Urban Technology*, Vol. 24 No. 1, pp. 3-27, doi: 10.1080/10630732.2017.1285123.

NAE (2018), *14 Grand Challenges for Engineering in the 21st Century*, The National Academy of Engineering, Washington, DC.

Nairne Schamne, A., Nagalli, A. and Soeiro, A.A.V. (2022), "Building information modelling and building sustainability assessment: a review", *Frontiers in Engineering and Built Environment*, Vol. 2 No. 1, pp. 22-33, doi: 10.1108/febe-08-2021-0038.

Nam, T. and Pardo, T.A. (2011), "Conceptualizing smart city with dimensions of technology, people and institutions", *Proceedings of the 12th Annual International Conference on Digital Government Research*, College Park, MD, June 12–15, pp. 282-291, doi: 10.1145/2037556.2037602.

Ning, Z., Huang, J. and Wang, X. (2019), "Vehicular fog computing: enabling real-time traffic management for smart cities", *IEEE Wireless Communications*, Vol. 26 No. 1, pp. 87-93, doi: 10.1109/mwc.2019.1700441.

Novieto, D.T., Kulor, F., Apprey, M.W. and Ayeke, E. (2023), "Appraisal of students' perceptions on green building concepts in a technical university", *Frontiers in Engineering and Built Environment*, Vol. 3 No. 2, pp. 122-136, doi: 10.1108/FEBE-08-2022-0034.

Ong, G.P. and Hwang, Y.H. (2019), "A concept for a smart, cool and naturalistic active mobility infrastructure landscape for Singapore", *2019 International Conference on Smart Cities*, Seoul, Korea, July 16–20.

O'Dwyer, E., Pan, I., Acha, S. and Shah, N. (2019), "Smart energy systems for sustainable smart cities: current developments, trends and future directions", *Applied Energy*, Vol. 237, pp. 581-597, doi: 10.1016/j.apenergy.2019.01.024.

Patrão, C., Moura, P. and Almeida, A.T.D. (2020), "Review of smart city assessment tools", *Smart Cities*, Vol. 3 No. 4, pp. 1117-1132, doi: 10.3390/smartcities3040055.

Pereira, P., Mendes, B. and Silva, L.T. (2019), "Methodology for individual air pollution exposure estimation based on data from air pollution concentration maps, daily routes and activities", *2019 International Conference on Smart Cities*, Seoul, Korea, July 16–20.

PWC (2022), "How digital twins can make smart cities better", available at: https://www.pwc.com/m1/en/publications/documents/how-digital-twins-can-make-smart-cities-better.pdf

Rani, S., Mishra, R.K., Usman, M., Kataria, A., Kumar, P., Bhambri, P. and Mishra, A.K. (2021), "Amalgamation of advanced technologies for sustainable development of smart city environment: a review", *IEEE Access*, Vol. 9, pp. 150060-150087, doi: 10.1109/access.2021.3125527.

Shahfahad, Naikoo, M.W., AIslam, R.M.T., Mallick, J. and Rahman, A. (2022), "Land use/land cover change and its impact on surface urban heat island and urban thermal comfort in a metropolitan city", *Urban Climate*, Vol. 41, 101052, doi: 10.1016/j.uclim.2021.101052.

Sousa, N., Lee, S. and Zhang, X. (2021), "Machine learning and artificial intelligence in municipal engineering", *Municipal Engineer*, Vol. 174 No. 2, pp. 65-66, doi: 10.1680/jmuen.2021.174.2.64.

Uddin, W. (2019), "Smart city opportunities and challenges related to connected infrastructure, disaster resilience, and climate adaptation", *2019 International Conference on Smart Cities*, Seoul, Korea, July 16–20.

UN (2018), "World urbanization prospects 2018", United Nations DESA/Population Division, available at: https://population.un.org/wup/

UN (2023), "Sustainable cities and communities", United Nations, available at: https://www.un.org/sustainabledevelopment/cities/ (accessed 22 December 2023).

USDOT (2015), *Laying the Groundwork for Smart Connected Cities*, Report published for UDOT by Volpe Center, Cambridge, MA.

USDOT (2018), "How does a 'smart city' operate? Integrated corridor management and the smart cities revolution: leveraging synergies", available at: https://ops.fhwa.dot.gov/publications/fhwahop16075/ch2.htm

Wang, H. and Meng, X. (2019), "Transformation from IT-based knowledge management into BIM-supported knowledge management", *Expert Systems with Applications*, Vol. 121, pp. 170-187, doi: 10.1016/j.eswa.2018.12.017.

White, G., Zink, A., Codecà, L. and Clarke, S. (2021), "A digital twin smart city for citizen feedback", *Cities*, Vol. 110 No. 1, 103064, doi: 10.1016/j.cities.2020.103064.

Woodhouse, J. (2015), "Briefing: standards in asset management: PAS 55 to ISO 55000", *Infrastructure Asset Management*, Vol. 1 No. 3, pp. 57-59, doi: 10.1680/iasma.14.00013.

World Bank (1994), *World Development Report 1994*, Oxford University Press, New York.

Xu, H., Omitaomu, F., Sabri, S., Zlatanova, S., Li, X. and Song, Y. (2024), "Leveraging generative AI for urban digital twins: a scoping review on the autonomous generation of urban data, scenarios, designs, and 3D city models for smart city advancement", *Urban Info*, Vol. 3 No. 1, p. 29, doi: 10.1007/s44212-024-00060-w.

Further reading

Fischer, J.M. and Amekudzi, A. (2011), "Quality of life, sustainable civil infrastructure, and sustainable development: strategically expanding choice", *Journal of Urban Planning and Development*, Vol. 137 No. 1, pp. 39-48, doi: 10.1061/(asce)up.1943-5444.0000039.

Harrison, C., Eckman, B., Hamilton, R., Hartswick, P., Kalagnanam, J., Paraszczak, J. and Williams, P. (2010), "Foundations for smarter cities", *Journal of Research and Development*, Vol. 54 No. 4, pp. 1-16, doi: 10.1147/jrd.2010.2048257.

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