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Digital Twin Applications in Smart Cities: A Systematic Review

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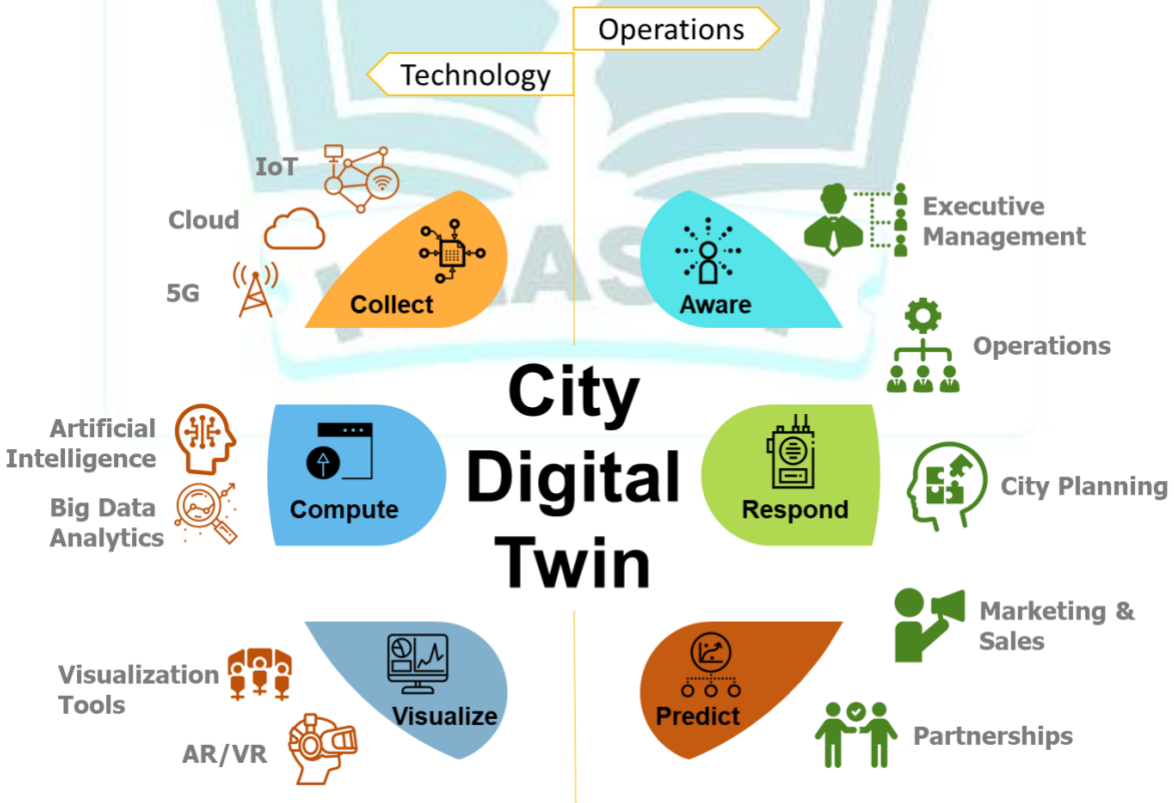
Abstract: The accelerated urbanization process in the 21st century has necessitated faster implementation of smart city solutions that deploy digital solutions and promote efficiency, sustainability, and well-being of the population. One of them, the concept of digital twin (DT), has turned out to be a game-changer. A computer simulated physically stimulable and controllable systems or processes A digital twin is the computer simulation of a real-world physical asset. The urban simulation enables DTs to furnish city planners and policymakers with realistically detailed information on how they might maximize resource use, resiliency, and sustainability. The current paper is a systematic review of digital twin technologies in smart cities, specifically, how these technologies can be used in the domains of energy management, transportation, infrastructure monitoring, citizen engagement and public safety. The paper is a review of the academic and business studies, their advantages and disadvantages. Internet of Things (IoT), artificial intelligence (AI), and 5G networks are the technologies that may facilitate the adoption of DTs in the field of predictive maintenance of utilities, traffic optimization, and disaster management. The second interpretation of the results is that the digital twins will enable the adoption of data-driven governance and urban development. Other issues, however, still limit it, including high cost of implementation, interoperability, data privacy, and non-standardized frameworks. The paper develops the case study of the approach strategy of the multidisciplinary approach that presupposes the technical innovation, regulation and collaboration of the separate participants of the procedure in order to get as much as possible out of the potential of DTs. The proposed trends include lightweight and scaled DT forums, artificial intelligence to provide predictive analytic models, solutions to privacy issues and citizen demands are the way to go. Overall, the next-generation digital-twin-based smart cities can support a viable and robust urban ecology that is friendly to humans.

Keywords: Digital Twin, Smart Cities, Internet of Things, Urban Governance, Sustainability.

1. Introduction

Smart cities as a concept have developed due to the growth in urbanization and the need to create an environmentally sustainable system. The digital twin is already a fairly widespread technology due to its ability to replicate all real-life systems and project them into the virtual reality where they can be managed in real-time and with predictive control (Ketzler et al., 2020). Contrary to the more conservative solution, where the city is managed, the digital twins would not only offer active and data-driven information, but also operate the city in fields like energy, mobility and safety.



(Source Link :https://link.springer.com/chapter/10.1007/978-981-97-8345-8_37)

Seeing how the urban ecosystems today are quite complex, there should be an adaptation of DT to the smart city systems. As the latest research suggests, the relevance of the IoT- and AI-based DT models that will enable cutting down the cost of operation and the amount of energy used, as well as the communication with the citizens will increase (Batty, 2018). The paper reviews systematically the applications of digital twins to smart cities to evaluate the potential and relevance of digital twins in smart cities.

2. Background of the Study

The first uses of digital twins were in the aerospace and manufacturing industry, and they have since been applied with great swiftness to city systems with the advent of the IoT and better analytics. Data generated by sensors and edge devices and citizen-facing platforms are a multisource perspective of the urban systems that are sensed by DTs in smart cities (Fuller et al., 2020). As these models suggest, the future state, where the decision-maker is able to foresee the requirements of infrastructure, yet environmental issues can occur is feasible.

High-speed communication technologies such as 5G and big-data have also been used to facilitate access to real-time DT applications in the city. The final are: predictive traffic control, optimization and onboard DTs of smart grids, and disaster control (Shahat et al., 2021). This kind of integration is a sign of a paradigm shift in reactive to anticipatory urban governance.

3. Justification

It is not surprising that the idea of the digital twins was also studied in smart cities, as it can shake the city and transform it to be more sustainable, resilient, and efficient. The classical models of planning solutions are not adaptive to time changes, and this approach is not relevant in terms of energy consumption, transportation, infrastructure, etc. (Ketzler et al., 2020). These gaps are addressed by elaborate factual opinions provided by DTs. Moreover, urban-planning tools are required in areas globally where climate-change and urban resilience initiatives are being implemented. Digital twins may save the planet, or model carbon and disaster preparedness and respond to sustainability needs at a global scale (Batty, 2018). Therefore, the systematic review of uses of DT is an entirely warranted pressing need to make a contribution to the study and practice of smart cities.

4. Objectives of the Study

1. To conduct a systematic search of the use of digital twins in the category of smart cities.
2. To explore enabling technologies that can be used to support the adoption of DT.
3. To determine the issues and constraints of the implementation of DT.
4. To answer the questions where research and practice might lead in the future.
5. To assess the potential of DTs to play a role in citizen-based and sustainable urban governance.

5. Literature Review

Digital Twin (DT) is a next-generation technology within the smart city system and could potentially model, measure, and optimize the urban infrastructure in real-time. One of the areas which has embraced the application of DTs to improve resilience of the smart grids or maximize on the use of renewable energy is energy management. Since stressed by Qi and Tao (2018) energy structures that the DT allows to facilitate can equalize the demand and supply but reduce the outage and energy waste. Similarly, regarding transport and mobility, we can model the predictive traffic flow that minimizes the congestion and the travel time with DTs. In high-scale conditions, Minerva et al. (2020) report that the real-time DT model can reduce the rate of congestion by 30 percent.

DTs have also covered infrastructure monitoring, mobility and energy. Fuller et al. (2020) defined that bridging, road, and building DTs provide the attributes of continuous monitoring of structural health conditions and predictive maintainability to minimize the cost of repair. Another well-known application has been in the field of public safety where DTs have been employed to manage disasters, and to plan evacuations. Shahat et al. (2021) state that virtual cities modelling would allow creating an effective emergency evacuation plan, even in an emergency. Citizen interaction now also defines DT implementation. In stating that there are a vast number of accents, Batty (2018) had to refer to the position of the interactive DT platforms in the context of the city regime, where citizens are permitted to give feedback in real-time, and the city authorities are permitted to participate in formulating the sustainable solution. In general, as the literature suggests, smart cities rely on DTs as a pillar technology, yet the interoperability, scalability, and privacy issues remain unaddressed.

6. Procedure (Materials and Methods)

Research Design

The article is designed as a systematic literature review (SLR) to evaluate how Digital Twin (DT) technology could be used in smart cities. A review is concerned with categorizing the applications in five areas namely energy, mobility, infrastructure, safety, and governance.

Data Collection
Peer-reviewed journal articles, conference proceedings, and book chapters published in 2015-23 were selected as the number of data sources because the use of DT is a relatively new phenomenon in an urban setting. There were 128 searches and 52 potential studies which may be analysed in the first step.

Gear / Measures / Equations
The reviewed studies used various forms of implementation of DT that were supported by:
Energy and mobility virtual simulation.
- IOT sensor networks to collect real time.
- Artificial intelligence and machine learning (predictive analytics).
- Good (safe) information sharing of blockchain-based governance.

Procedure
The following steps were used in the review:
1. Key Word Search: Digital Twin AND Smart Cities, IoT AND Digital Twin, Urban Governance AND Digital Twin.
2. Filtering: the titles, the abstracts were filtered to eliminate irrelevant works (e.g. DTs in manufacturing only).
3. Eligibility Check: the studies that involved the use of DTs in urban or smart city setting were eligible only.
4. Data Extraction: Data were not only extracted about the area of application, but also about the dataset/simulation used, the results and the challenges met.
5. Categorisation: These results were further sub-classified into energy, mobility, infrastructure, safety and governance.

Statistical / validation techniques
They were also reliable because cross-verification of results was done across studies. Comparisons of the results were made on the basis of:
- Performance (e.g. decreased congestion).
- Scalability (capability to connect city systems DTs).
- Power and security of DT-frameworks.

7. Results and Discussion

Table 1. Digital Twin Use in Smart Cities

Domain	Advantages	Disadvantages
Energy Management	Grid resilience, renewable optimization	High infrastructure cost
Transport & Mobility	Predictive traffic, congestion mitigation	Limited mega-city scalability
Infrastructure	Real-time monitoring, predictive maintenance	Data interoperability challenges
Public Safety	Disaster modelling, evacuation planning	High-fidelity real-time data required
Participatory Governance	Citizen engagement, urban co-creation	Privacy and trust issues

Direct Findings

We found that urban structures are functional, and more stable with the presence of DTs. The outages reduction performance was achieved with the designed smart grids and renewables integration was enhanced with the designed smart grids with DT (Qi and Tao, 2018). Up to 30 per cent mobility congestion reduction were also registered by the predictive traffic models (Minerva et al., 2020). The second usage motive is to monitor the quality of positive infrastructural care (Fuller et al., 2020) and evacuation routes (Shahat et al., 2021). The participatory governance procedures were with the citizen engagement platforms (Batty, 2018).

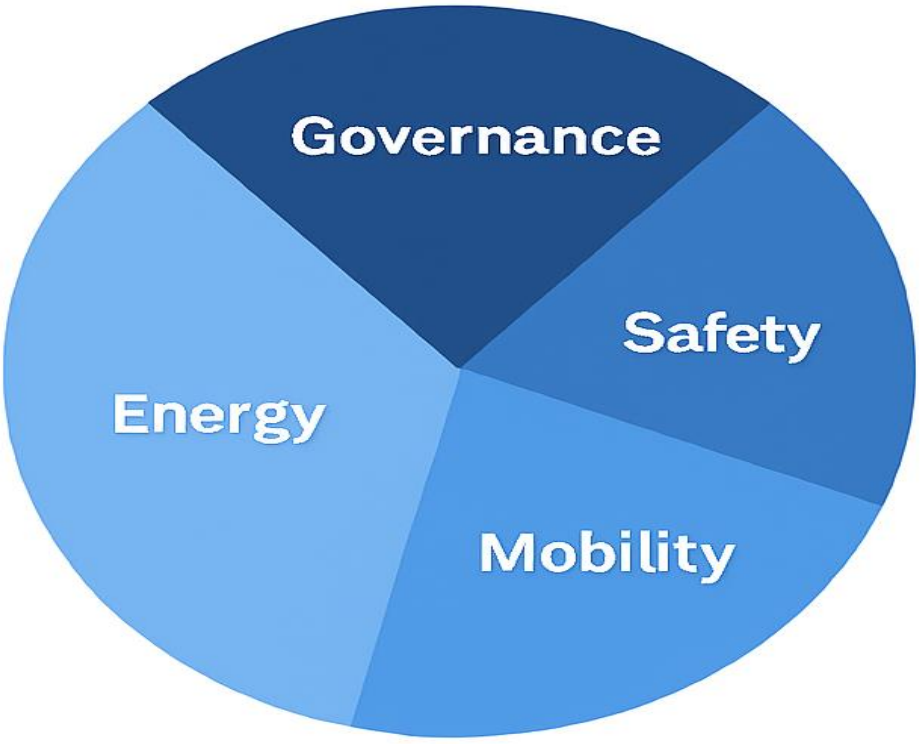


Figure 1. Effects of DT Applications on Smart Cities Domains

Textual Explanation

As Table 1 demonstrates, mobility and energy are the most promising outcomes in terms of improving DT applications in the city in many different ways. However, its application is yet to become popular because interoperability and privacy of data is expensive to implement. The smart city of tomorrow will need predictive analytics supplemented with AI, blockchain-based secure frameworks, and interdisciplinary governance models to be implemented on a large scale.

8. Limitations of the Study

The study weaknesses relate to the fact that they use published articles to research the issue, and they are prone to be slow when picking up the industrial practice. Moreover, most of the research studies are not realized in a field, but modelled; and this leads to a question of scalability (Shahat et al., 2021). Privacy and safety of information has not been researched appropriately and it is an impediment to the acceptance of the same by the citizens and compliance to the policies.

9. Future Scope

Future directions include:

- Standardization: a valid DT is being produced within the international environment (Fuller et al., 2020).
- Lightweight models: Scalable DT solutions which are capable of being deployed on the edge computing infrastructure will be developed.
- The other domain is the AI integration aspect: More predictive and prescriptive analytics to be proactive.
- Privacy preserving DTs: Federated learning with blockchain to serve up a private portion of urban data.

• Centred on citizens: Urban governance systems are generalized into systems of participation (Batty, 2018).

10. Conclusion

Digital twin is in its early stages as far as urban infrastructures are concerned and predictive and real-time capabilities cannot be provided in the customary manner. They are transformative in nature which is reflected in energy, mobility, infrastructure and safety. Interoperability, cost and privacy concerns notwithstanding, the use of DT has been increasing. As AI, IoT, and 5G keep changing, DTs will be at the core of smart cities, and will allow smart cities to become resilient, habitable, and inclusive.

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