CE441B Construction Management

DIGITAL TWIN OF CITIES

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1 Introduction

1.1 Construction 4.0

In the 21st century the concept of Industry 4.0 or the 4th Industrial Revolution (4IR) came up that made a great deal of technological and scientific advances. The focus was on using computers and cyber-physical systems. The construction industry learned from this progress which resulted in the term Construction 4.0 in 2016. This term has gained popularity in the recent few years. With the advent of Construction 4.0, construction industry is expected to become more technologically advanced and enhanced in a way we can solve most of our major problems by sitting on a computer system. Construction 4.0 involves the use of the advanced technologies like Building Information Modeling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI) in construction processes. BIM is a detailed digital representation of buildings, fostering collaboration and reducing errors. IoT are the devices that have sensors and processing power for efficient data exchange, improving monitoring and control on construction sites. AI helps to make intelligent data driven models to analyze the data and optimize decision-making to enhance overall project management in the construction industry.

The Construction 4.0 framework provides a mechanism via which we can digitally model the built assets that we have in our physical world, design new assets in the backdrop of what already exists in our environment or plan for the retrofit and rehabilitation of existing assets using these digital models in a planned and informed way and once these assets are digitally captured and designed, we can also make use of the digital and physical technologies to deliver these physical assets to the citizens.

There are also a few literatures discussing the emergence of Construction 5.0. The human-robot collaboration with a vision of harmonious cooperation between humans and robots is the concept behind Construction 5.0. Collaborative robots (cobots) are seen as robots designed for safe interaction with human workers in the coming generation within this domain.

1.2 Why is Digital Twin chosen as topic?

A Digital Twin is a dynamic real time virtual representation of a physical asset, such as a building and extended to infrastructure and cities as well. In this report, the focus is on Digital Twin of cities. This topic is chosen because I find this concept interesting, and it has got a lot of potential in the coming years. I want to go for higher studies in LiDAR and Remote Sensing that can be used to scan and sense the physical world, an application in this discipline. So, I wanted to get an overview of digital twins. The concept of Digital Twin is a very broad. However, I believe that through this report I will be able to develop at least a basic understanding of this concept that will add some value towards my career goal of becoming a professor. This concept holds utmost potentials to transform the world, so it fascinates me a lot like the scientific theories used to do when I was a child.

2 Academic Research Perspective

2.1 Digital Twin

Digital Twin is a real-time replica of a physical asset in construction industry. DT has a dynamic nature and reflect real-world changes with the help of data collected using a lot of sensors like LiDAR, Camera, GPS, sensors for motion, temperature, pressure, and a lot more to get an unprecedented insight into the physical world. DT extend their reach beyond mere buildings, and they encompass entire objects or systems, such as buildings, campuses, cities, transport networks like railways and more. DTs are developed for simulation, testing, monitoring, and maintenance purposes throughout the product lifecycle of the physical asset. The basic idea of developing DT is that it supports better decision making and helps predict future through data driven simulation models.

DT of a city is an interconnected system of various digital twins in a city including the buildings, transportation network and the population living in the city. These digital twins support synchronization of the real state of the city through data from various DT instances within a city. City DTs integrate with their sub-DTs and intelligent functions (e.g., AI, machine learning, and data analytics, among others) to create digital simulation models that are able to learn and update from multiple sources and to represent and predict the current and future condition of their physical counterparts correspondingly and timely.

2.2 Historical Perspective

Origin & Evolution of Digital Twin

The idea of Digital Twin was first given by Dr. Michael Grieves in the first executive Product Lifecycle Management courses at the University of Michigan in 2002 (Grieves 2005, 2014, 2016). Grieves proposed the digital twin as the conceptual model underlying product lifecycle management (PLM).

The concept of DTs originated from the aerospace industry when National Aeronautics and Space Administration (NASA) published a roadmap report on modeling and simulation in 2010, where they provided the first definition for DTs. The digital twin concept, which has been known by different names (e.g., virtual twin), was subsequently called the "digital twin" by John Vickers.

Evolution of Digital Twin

Earlier the focus of Digital Twin was primarily on using digital representations to simulate and analyze construction processes. Over time the scope has extended to the possibilities of real time monitoring, predictive maintenance and enhanced decision making across the entire lifecycle of built assets like buildings, infrastructures, and cities. Now digital twin has evolved to integrate data from various sources to improve city management and sustainability. The evolution of digital twin represents a shift from the static representation to dynamic data driven models in the construction.

2.3 Key Components of Digital Twin

A digital twin consists of three major components:

1. Physical real-world object/process and its physical environment
2. Digital Representation of the object/process
3. A communication channel established between the physical and the virtual representations for continuous synchronization through sensors, algorithms, simulation models, correlations, etc.

In the context of Digital twin, there are three main capabilities that are also discussed viz, mirroring, shadowing, and threading.

Mirroring

'Mirroring' means creating a virtual representation of the physical asset that we have say buildings, infrastructures and cities. This makes use of Computer Aided Designing (CAD), Laser Scanning (LiDAR), Photogrammetry, Building Information Modelling (BIM), etc.

Shadowing

'Shadowing' implies to reflect or shadow the real-world changes happening in the physical asset and send them to the virtual world for enhanced analysis. Synchronization between real world object and virtual world requires use of various sensors like Cameras, LiDAR, RADAR, sensors for temperature, pressure, and a lot of other IoT sensors. It also implements techniques and algorithms of Model Matching, Data Association, Reinforcement Learning, etc.

Threading

'Threading' refers to the capability to connect the different operational stages and different digital twin instances. It creates a kind of connection (called digital thread) between various instances of digital twins so that details of upstream and downstream processes are well informed to all the subsystems. Through use of digital thread, a machine can learn about the operating condition of all the other subsystems. This way the overall DT can gather all the required information of all the instances within the system. This is usually implemented with the help of algorithms and technologies like IoT sensors, Machine Learning, Fleet Learning, etc.

2.4 Addressing Focus Areas of Construction Management

Construction Management is important for any construction project because less than 20% of the construction projects meet their project goals in terms of time, cost, safety, and quality. One or the other goal is left unachieved or compromised in various construction projects. With the advent of Digital Twin technology, various focus areas of construction management viz, Time, Cost, Safety and Quality can be effectively addressed.

Time Management

Digital twin can do real-time monitoring of the construction site and data analysis helps us predict potential delays and bottlenecks well in advance so that we can work accordingly. Integration of DT with scheduling tools can help effectively manage project timeline.

Cost Management

Accurate data from digital twin can help estimate project cost and budget effectively and analysis can help estimate the overruns as well. This prevents rework and optimize resource allocation which ultimately lead to reduced cost. The inefficient techniques can also be eliminated. Thus, Digital twin helps monitor resources utilization effectively to manage and control the cost of the project.

Safety Management

The analysis of construction site condition and identification of potential hazards can be from done through digital twins. Real time monitoring can enhance the safety of workers in field by alerting and notifying them as and when required. If there is a possible fault in any subsystem or component of the system, then safety measures can be addressed well in advance.

Quality Management

Digital twin can do comparison of the digital model with the physical structure. If there are any faults in quality standards of any instance then digital twin can prompt and address the quality issues, thus leading to quality control of the entire system to meet its quality goals.

2.5 Current Research Trends

One major benefit of the city digital twin is connecting past and present information and future scenarios. The ability to integrate several data models across time and space and present the information on a single 3D model. This enriches the exploration, understanding, and foreseeing of current and future trends of the city's operations. Currently, the level of development that has been reached so far can improve city data management, digital visualization of the city, awareness of several spatiotemporal situations, predictions of future scenarios, and integration of the city domains and stakeholders.

This concept of DT of a city is a very broad idea and researchers have focused on the specific areas of this broad concept. Research work on the data side of the DT for example is about what data format to use to store data, how to convert one format data to another format data, how to integrate two data formats into one data format, how to make a general standard data format to store various data file information, what data format to use to develop a digital twin, etc. The data analysis side of DT include works for example on how to analyze the data that we have and make DT sense of the physical world through the virtual world, how to extract meaningful information from the large amount of data. How to process data, how to utilize AI for predictive analysis, how to clean data, etc. Research work on integration aspects of DT for example include how to integrate the real time data for enhanced project monitoring, how to add interactivity in BIM, how to explore the augmented reality applications for on-site construction work, etc. Visualization of data after processing is also a research trend among researchers. The research is now on sustainability and environmental management as well in a way to optimize the use of resources and take best control of everyday infrastructure. A smart city approach is perceived to boost the sustainability of cities environmentally and economically and improving the delivery of services to their inhabitants.

3 Industry Perspective

3.1 Introduction

The foundation of Digital Twin in construction is BIM that is essentially a digital model of a building that contains all bits of information, not only a 3D representation but also intricate details such as materials, dimensions, etc. But the shortcoming of BIM is that it is static in nature and the real-world changes are not reflected to the virtual digital model. To address this issue the concept of digital twin came into existence in industry as a BIM with interactivity in the sense that there is interaction between the real world and virtual world due to which the changes in physical world can be reflected to the digital model through sensors and algorithms. Throughout the time Digital Twin has evolved and extended its meaning not only to buildings but a set of buildings, transportation network and even cities.

The most promising idea is the 'city digital twin' — a realistic simulation of a city, including the transport network and population. The twin should accurately model changes with the passing of time, given initial conditions, while being reactive to changes and interventions, such as new transport services, new housing developments or changes to fares. The city digital twin can be maintained, updated, and extended — potentially remaining relevant for as long as the city is inhabited.

A true urban digital twin consists of multiple layers. The first is a digital replica – the digital city. Adding data from IoT creates the second – the connected city. Applying AI and simulations to that data produces the third – the intelligent city.

- Digital city: Serves as the foundation for any urban digital twin by providing the necessary data to create a virtual model of the physical city.
- Connected city: Allows for real-time monitoring, analysis and control with interconnected devices that communicate with each other.
- Intelligent city: Works at the core of the urban digital twin with a platform that can connect to and visualize all data from the digital city and the connected city and enables analytics, AI and simulations.

3.2 Current Employments and Adoption

In its simplest form, a digital twin describes a model of an asset that has the engineering detail embedded and coordinated within it that enables engineering and construction firms to perform integrated design and coordination. This is a simple and basic interpretation of a digital twin considering only static data from a single process or area or facility, level 1 one can say.

The outcome achieved here is that the construction director has an excellent digital twin of what has been built and accurately represents what will be handed over to the maintenance team.

Building on this model, now owned by a maintenance business unit or director, a level 2 digital twin would gather historic usage data and deploy analytics to start to look at scenarios that could deliver improvements to the physical asset or predict things that are going to happen so that these risks and issues can mitigated in advance. This would allow an asset owner to move from a break fix scenario to a predict and prevent model saving maintenance cost and potentially future capital cost through engineering the solutions to actual needs rather than perceived needs or historic engineering standards as well as potentially extending the life of the asset.

A level 3 model could add in real-time data from a currently deployed situation to be able to look at scenario planning in real-time to optimize the use of the asset making significant maintenance savings and adapting to the actual use of the building. This could all be fed back into the model to simulate any asset replacement or other asset works in the model and choose the optimized solution based upon the customers prioritized requirements.

These three levels would then be the foundation to start to build a more complex and business realistic model by starting to add linked data sets, including weather data to predict how plant may need to perform or occupancy data to look at optimizing environmental aspects within the asset. This scenario only considers the model from a building and maintenance point of view yet there are significant gains to be made in adding in the operational data particularly when considering a retail mall, airport, railway station or hospital. Moving to a level 4 digital twin one could bring in this operational data (built up in the same way as described previously) to:

- Support decision making and optimization of the day-to-day operation.
- Make recommendations as to how best to bring a disrupted operation back into normal operation
- Make recommendations as to how and where to improve passenger, customer or staff experience
- Advise on how to increase revenue

A level 5 digital twin could bring in more data from alternative sources that place this digital twin in its situational context and start to look at this as a system in real-time. This could include people and how they behave, the interaction between surface access and the landside operation in airports or transport data, logistics data and weather data.

Following this one could move a building or operational asset into a set of connected assets and then combine datasets across planning, operations, building and maintenance to deliver a rich virtual representation of the physical environment. This is where a city-wide model could really start to offer value to understand the nuanced interactions between parts of a city and be used to offer optimized solutions to the impacts of significant decisions like a new runway at a city airport or a high-speed train line and the potential knock-on impacts to local transport infrastructure, retail, urban developments and health and wellbeing.

3.3 Case Studies

Increasing Safety and Government Transparency in City of Baton Rouge, USA

The City of Baton Rouge used DT to enhance government transparency and safety by addressing blighted properties, lost revenue, and crime data challenges. They integrated existing GIS data with financial and citizen request data. This way they increased transparency and accountability, improved decision-making in various city departments and showcased the power of DT in smart city.

Improving sustainability of urban green spaces by SISPI SpA in Palermo, Italy

SISPI SpA used DT to improve the sustainability of urban green spaces in Palermo, Italy. It enhanced the efficiency and sustainability of maintaining public green areas. They developed the Urban Green Spaces Monitoring Tool using Copernicus satellite data. The tool classifies green spaces based on vegetative stress and calculates its vegetation stress index which gives information about the irrigation needs, especially during the drought conditions. Thus, reducing ground inspections, maintenance, and planning costs, contributing to city's sustainability.

Revolutionizing Urban Wastewater Management in City of Cologne, Germany

Hexagon implemented a GeoAI solution to optimize city wastewater operations. DT developed by them detects changes in paved surfaces impacting drainage that enhances efficiency for the municipal wastewater authority. It calculates precise wastewater taxes on private lands. This way it contributes to urban infrastructure management.

Urban Planning in Virtual Singapore

They developed a city digital twin through the Virtual Singapore program, where the idea was to synergize all the 3D efforts into a unified platform for a more collaborative environment for all public agencies, in addition to citizens, the private sector, and research institutions. The model facilitates better visualization of the city/state, real-time collection of information and analysis, and simulations and "what if" scenarios for enhanced planning and decision-making. It can be perceived as a very significant city digital twin.

Digital Twin of Stuttgart, Germany

Stuttgart is an exemplary model of how cities can solve today's most pressing urban challenges, such as sustainability, safety and mobility, through the use of real-time data analysis. The solution they have proposed will provide a common operating picture for monitoring sensor values, such as water quality, flood levels and parking space occupancy, enabling the city to derive insights for optimizing operations and making informed decisions for the future.

3.4 Benefits and Challenges

Benefits

Digital twins hold promise to improve decision making and investment for a broad spectrum of stakeholders, from city-scale transport planners to individual building owners. Potential benefits include everything from better health and wellness in office environments to improved air quality in our dense urban environments. With the digital and social landscapes converging in terms of modelling, sensing and inclusivity, digital twins may be the technology to help deliver on these challenges.

The benefits of digital twin of a city (but not limited to) are following:

- Monitoring of the current state of the urban environment like wear and tear and condition of bridges, streets, & urban infrastructure to ensure timely maintenance & extended service life.
- Accurate measurement of distresses on pavement and real time monitoring of the pavement condition predicting the precise rutting and fatigue life of the pavement.
- Improving the situation on the roads and saving fuel through smart traffic lights and road markings.

- Smart surveillance cameras for crime tracking and automated alert system in real-time.
- A smart irrigation system in parks and public areas that considers weather conditions and current conditions.
- Optimization of snow removal operations thanks to real-time data about the situation on the roads, weather conditions and the nearest snow removal vehicles.
- Microclimatic weather forecasts based on an urban sensor network.
- Rational energy consumption thanks to city lighting on demand.
- Pollution control and regulatory impact analysis through an environmental survey.
- Smart parking solutions that automatically find the best parking spot.

Challenges

Despite promising advancements DT face challenges – technical, legal, and cultural hurdles. We now live in a world where data affects every facet of our lives, that raises the urgent question of what kind of data, and in what amounts we must collect to achieve our desired outcomes. While data-driven decisions are only as good as the data collected, the answer to this question is not always clear in advance. For instance, how do we collect emotional data of employees and use that data to adjust the environmental parameters of the building, to promote more productive and happier workspaces? How much data do we need from each individual, and can we trust its fidelity once we have it? The designs of and inputs to our digital twins are ever changing, and the twins must adjust to the changing parameters.

With regard to data storage, more organizations of all sizes are moving to the cloud for strategic, financial and operational flexibility and scalability. Given this shift, we need to consider how we use, build, and operate our digital twins, and how we handle their vital role in the consumption, computation, storage and management of information. There are a lot of sensors involved that are very costly as well as require specialized knowledge. New skills and talent must be brought in, new training infrastructure must be created, and cultures must change. Security and privacy are key for those operating digital twins as well as for those interacting with them. Cyber security is always a challenge. We need to consider data governance, open standards, APIs, privacy, intellectual property and cybersecurity. At present, the information assets of many organizations may not be properly managed and secured. Each organization will need to develop appropriate policies and practices. Location data is generally highly desirable, and when properly collected can be a major aid in smart city planning and development. However, data anonymization remains a challenge.

One of the most obvious interactivity modalities for DTs is to view them, which immediately implicates cartography and geovisual analytics, as well as current practices in video game and computer animation visualization. This cartographic problem is yet another challenge as to how to visualize the Digital Twin. The integration of data from various digital twins within a city and from various sensors, BIM, AR into a coherent digital twin of a city is also very complex. True integration remains a challenging proposition, and the successful and secure integration of digital twins will require more research and development before the industry reaches a state of maturity and understanding.

4 Comparative Analysis - Academics vs. Industry

4.1 Lag between Academia and Industry

Although city digital twin research is still in its infancy, with robust research linking digital twins to city-scale modeling starting very recently, it shows a rapid pace of development towards fully utilizing digital twin technology in the advancement of cities. Within the concept of digital twin of cities, academic research has surged ahead of industry. The academic research has a lot of models and literature that can solve so many real-life problems and help in urban planning, sustainability and overall city management. Academia has proposed literature about sensors for taking data, formats for storing data, algorithms to convert data from one format to another, models to access and analyze data, software with integration models to visualize the combined data on a dashboard, algorithms to connect two digital twins and integrate them and a lot more. The industry practices seem to be lagging behind the theoretical advancements proposed by academicians and researchers. Industries have implemented few modalities of the digital twin but still the full potential discussed and outlines by academicians is yet to be realized in the industry practices. While this may be due to the reason that implementing the theoretical models proposed by researchers is always not practical so the academicians and researchers should discuss and interact with industries to understand what practical problems or challenges they are facing in implementing the various models and resolve those problems through their research work and refine their literature to better suit the real world and make them more adaptable and applicable.

4.2 Bridging the Gap

The gap between academia and industry is evident from the modality and functionality of the level of adoption of digital twins in industries. The digital twins that industries have developed have not yet reached the level of a complete digital twin since, for example, the flow of information is still one-way from the physical side to the digital.

Researchers can enhance the efficiency of data acquisition and processing. Academia has proposed standardization of the data models or the utilization of open standards, which are not widely used yet by the industries worldwide. Industries should make use of these open standards to store, analyse and process data collected from DT scenarios. However, data standards cannot be generalized easily due to the diverse methods, data generated within city domain and software that used in the development of city digital twin. Generalized data standards will facilitate data management and interoperability among the various domains of DT instances.

The literature present on digital twin is very diverse and there is lack of uniformity among different domains. Different scholars can collaborate together with the industries and conduct several seminars and conferences to discuss and develop some uniform models for the development of city digital twin so that industries could adopt these comprehensive and uniform digital twin models and reach full potential of City Digital Twin.

Bridging the gap between academia and industry requires mutual understanding and symphony between both. Industry can implement the models and research work proposed by academia. The real-life practical challenges encountered by them can be then well communicated with the complexities of digital twin to the academic world. Academicians and Researchers then can address these real-life practical issues that are faced by the industry. Addressing these practical issues will refine their theoretical models and frameworks to better serve the real-world scenario and act as a roadmap to develop a full-fledged city digital twin.

5 Proposal

Digital Twin of Nation

One of the key recommendations is to develop a so-called national digital twin. Fundamentally one should know that a national digital twin is not a single monolithic model of a whole nation's infrastructure but consists of digital twins that are constructed in different scales (e.g., individual asset scale, network/system scale, and city scale), built for various purposes and using different approaches, that are connected together, and all built on data. The idea of making the digital twin of nation and allowing for sharing of essential information from one part to another through some alert or notification system during times of crisis, emergency, accidents, disaster, etc. that will lead to better management and planning of nation's resources and infrastructure. The idea to include Environmental Impact Assessment in Digital Twins can help reduce carbon footprints and meet the sustainable development goals. With Digital Twin of Nation, there'll be order in the nation, when there'll be order in the nation then there'll be peace in the world. So, we can be happy and peaceful with this technology that can solve a lot of big problems and challenges faced by our nation.

Digital Twin of Earth

This concept of Digital Twin of nation can be later extended to develop a Digital Twin of Earth along with the network of satellite constellations. The Earth Digital Twin will also not be a single monolithic model of the whole earth but consisting of digital twins of several nations and that too digital twins that are constructed at various scales and built for various purposed together synchronized in a complete earth model. This way we can better organize the resources within earth and plan the space missions and observation to study the universe and understand the earth better for our own existence.

Although this concept is way too more advance and seem very impractical but if we can build and develop digital twin of several places and several sectors then this concept of Digital Twin of Nation and Digital Twin of Earth can also be realized in the generations to come. Digital Twin of buildings and infrastructure can integrate into a digital twin of cities. Digital twin of several cities within a state can be integrated into a digital twin of a state. Digital twin of several states can be then integrated to develop a digital twin of a nation. When all the nations agree to develop a secure and confidential digital twin of several nations combined to unleash the power of digital twin of our earth which after integrating with the satellite constellations of several countries will give us the digital twin of our whole earth system along with all its satellites and observatories. This requires a great deal of work by scientists, researchers, and industries throughout generations to achieve but one day this can be made possible with the technological advancements and hard work put in by researcher and industries day in and day out.

References

1. Grieves, M. (2014). "Digital Twin: Manufacturing Excellence through Virtual Factory Replication." *Digital Twin White Paper*.
2. E. Forcael, I. Ferrari, A. Opazo-Vega, and J. A. Pulido-Arcas, “Construction 4.0: A Literature Review,” *Sustainability*, vol. 12, no. 22, p. 9755, Nov. 2020, doi: 10.3390/su12229755.
3. S. Ivanov, K. Nikolskaya, G. Radchenko, L. Sokolinsky, and M. Zymbler, “Digital Twin of City: Concept Overview,” in *2020 Global Smart Industry Conference (GloSIC)*, Chelyabinsk, Russia: IEEE, Nov. 2020, pp. 178–186. doi: 10.1109/GloSIC50886.2020.9267879.
4. Q. Lu *et al.*, “Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus,” *J. Manage. Eng.*, vol. 36, no. 3, p. 05020004, May 2020, doi: 10.1061/(ASCE)ME.1943-5479.0000763.
5. 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, doi: 10.3390/su13063386.
6. Y. Jiang, S. Yin, K. Li, H. Luo, and O. Kaynak, “Industrial applications of digital twins,” *Phil. Trans. R. Soc. A.*, vol. 379, no. 2207, p. 20200360, Oct. 2021, doi: 10.1098/rsta.2020.0360.
7. M. Singh *et al.*, “Applications of Digital Twin across Industries: A Review,” *Applied Sciences*, vol. 12, no. 11, p. 5727, Jun. 2022, doi: 10.3390/app12115727.
8. Z. Wang, “Digital Twin Technology,” in *Industry 4.0 - Impact on Intelligent Logistics and Manufacturing*, T. Bányai and A. Petrilloand Fabio De Felice, Eds., IntechOpen, 2020. doi: 10.5772/intechopen.80974.
9. H. Wang, X. Chen, F. Jia, and X. Cheng, “Digital twin-supported smart city: Status, challenges and future research directions,” *Expert Systems with Applications*, vol. 217, p. 119531, May 2023, doi: 10.1016/j.eswa.2023.119531.
10. A. Zhang, J. Yang, and F. Wang, “Application and enabling technologies of digital twin in operation and maintenance stage of the AEC industry: A literature review,” *Journal of Building Engineering*, p. 107859, Oct. 2023, doi: 10.1016/j.jobe.2023.107859.
11. O. C. Madubuike, C. J. Anumba, and R. Khallaf, “A review of digital twin applications in construction,” *ITcon*, vol. 27, pp. 145–172, Feb. 2022, doi: 10.36680/j.itcon.2022.008.
12. M. Jafari, A. Kavousi-Fard, T. Chen, and M. Karimi, “A Review on Digital Twin Technology in Smart Grid, Transportation System and Smart City: Challenges and Future,” *IEEE Access*, vol. 11, pp. 17471–17484, 2023, doi: 10.1109/ACCESS.2023.3241588.
13. ‘Urban Digital Twin: Beyond the buzzword’. https://hexagon.com/go/sig/urban-digital-twin
14. *ARUP* on ‘Digital twin: towards a meaningful framework’. https://www.arup.com/perspectives/publications/research/section/digital-twin-towards-a-meaningful-framework
15. *Hern Alex’s* ‘Anonymised data can never be totally anonymous, says study.’ Published in *The Guardian*, 2019.
16. *Hexagon’s* ‘Improving sustainability of urban green spaces in Italy’. https://hexagon.com/resources/resource-library/Improving-sustainability-of-urban-green-spaces-in-Italy
17. Dassault Systèmes 3DEXPERIENCity® - *Virtual Singapore: Singapore’s Innovative City Project*. https://www.3ds.com/insights/customer-stories/virtual-singapore
18. *Autodesk’s* ‘Smart Cities for the Public Good’.
19. "Japan: Hexagon, Fujitsu Support Stuttgarts Urban Digital Twin Project." *MENA Report*
20. "Newcastle's 'Digital Twin' for Disaster Planning" published January 2, 2019.