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Η Τεχνολογία των Ψηφιακών Δίδυμων. Οι τομείς που εφαρμόζεται, εστιάζοντας στις έξυπνες πόλεις και στην Διακυβέρνηση.

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UNIVERSITY OF THE AEGEAN
ENGINEERING SCHOOL

INFORMATION AND COMMUNICATION SYSTEMS ENGINEERING DEPARTMENT

POSTGRADUATE STUDIES PROGRAMME
MSc IN e-GOVERNMENT

The Digital Twins Technology. The implementation sectors, focusing on Smart Cities and Governance.

DIPLOMA THESIS

by

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Acronyms

DT	Digital Twins
DUT	Digital Urban Twins
AI	Artificial Intelligence
ML	Machine Learning
IoT	Internet of Things
BIM	Building Information Modeling
CIM	City Information Modeling
API	Application Programming Interface
UAV	Unmanned Aerial Vehicles
IOC	Intelligent Ccity Operation Centre
CEC	Citizen Energy Communities
OEM	Original Equipment Manufacturer
ITS	Intelligent Transport Systems
V2E	From Video Frames to Realistic Events
PV	Photovoltaics
AFRL	Air Force Research Laboratory
IEQ	Indoor Environment Quality
PLM	Product Lifecycle Management

Περίληψη

Η τεχνολογία του Ψηφιακού Διδύμου έχει εισέλθει σε μια φάση ταχείας ανάπτυξης. Χρησιμοποιείται ήδη σε διάφορα συστήματα και τομείς. Οι εφαρμογές των Digital Twins τεχνολογιών βρίσκονται ήδη σε εξέλιξη και πιστεύεται ότι θα αναπτυχθούν ακόμη πιο γρήγορα τα επόμενα χρόνια. Οι τεχνολογίες των Ψηφιακών Διδύμων επιτρέπουν στους ερευνητές να δημιουργήσουν ένα εικονικό αντίγραφο ενός πραγματικού συστήματος και επομένως παρέχουν μια πλατφόρμα για την ανασκόπηση των δραστηριοτήτων, των αλληλεπιδράσεων και των συνεπειών διαφορετικών αποφάσεων εντός του πραγματικού συστήματος. Αυτή η τεχνολογία έχει ξεκινήσει έναν μεγάλο αριθμό ερευνών που παρακίνησαν αυτή τη διατριβή να ανακαλύψει τι ακριβώς είναι η Τεχνολογία των Ψηφιακών Διδύμων. Επιπλέον, πρόκειται να αναλυθούν οι περιοχές ανάπτυξης και ποιοι είναι οι βασικοί τομείς που εφαρμόζεται η τεχνολογία. Από αυτούς τους τομείς, αυτή η μελέτη εστιάζει στα Digital Urban Twins που εφαρμόζονται σε πόλεις, κωμοπόλεις, χωριά, δήμους, περιφέρειες και ακόμη και σε επίπεδο χώρας, με αναφορά στο τι μπορεί να επιτευχθεί μέσω της συνένωσης των DUTs με πρωτοποριακές εξελίξεις σε άλλες τεχνολογίες όπως π.χ. Τεχνητή Νοημοσύνη, Internet of Things και άλλες, με αποτέλεσμα να προτείνουμε νέες εφαρμογές και υπηρεσίες για έξυπνες πόλεις και περιοχές του αύριο. Θα διερευνηθεί επίσης ο τομέας της Διακυβέρνησης σε συνάρτηση με τον Ψηφιακό Δίδυμο με υπόσχεση νέων υπηρεσιών και ψηφιακών μέσων για τους πολίτες, σε μια προσπάθεια αντιμετώπισης των περισσότερων προβλημάτων και παροχής νέων υπηρεσιών σε κάθε είδους ζωή.

Abstract

Digital Twin (DT) technology has entered a phase of rapid development. Already used in various systems and areas. The implementation of Digital Twin is already underway and is expected to grow even faster in the coming years. Digital twin technology allow researchers to create a virtual duplicate of a real system, thereby providing a platform to review activities, interactions and consequences of various decisions within the real system. This technology has initiated a large number of surveys that have motivated this thesis to find out what exactly the digital twin technology is. In addition, the developments of Digital Twins and the key sectors thereof are analyzed. Out of these sectors, this study focuses on Digital Urban Twins being implemented in cities, towns, communities, regions and even at country level, with reference to what can be achieved by convolution of DUTs with breakthrough developments in other technologies with exponential growth, such as Artificial Intelligence, Internet of Things etc., leading to new applications and services being proposed for the smart city and region of tomorrow. Also, the sector of governance, with the promise of new services and digital means for citizens, will be explored to address most of the problems and provide new services for all ways of life. The Diploma Thesis is structured as follows: The Diploma Thesis is structured as follows: Chapter 1 introducts the Digital Twin Technology with presenting its history, its properties and the challenges that exist. Chapter 2 presents a synopsis of Key sectors that the Digital Twins implementing, ending with the benefits of each sector. Chapter 3 deepens in the concept of Digital Urban Twins and on the current Digital Urban Twins projects and prototypes in cities around the world. Chapter 4 is focusing on how Digital Twin enhancing e-governance and helps cities realize real-time remote monitoring, allows more effective decision-making and encouraging citizen's participation. Chapter 5 includes outlooks and research directions for Digital Urban Twins. Chapter 6 includes the general conclusions of the Thesis and in this chapter the appendices and the references which have been used are presented.

Keywords: Digital Twins, Digital Urban Twins, Internet of Things, Artificial Intelligence, Smart Cities, Digital Governance, Urban Governance, Urban Planning

Context and Aims of the Diploma Thesis

Digital Twin (DT) technologies are already being used in various systems and industries such as manufacturing, construction, healthcare, aerospace, transportation, smart cities, etc. DT technologies make it possible to create a virtual duplicate of a real system and thus provide a platform to examine activities, interactions and consequences of different decisions within the real system. DT technologies are used in industry to improve the productivity, efficiency, availability and thus the quality of a plant or service. By considering cities as a complex system, there are and will be numerous applications linked to the underlying technologies to develop Digital Twins. Also, the inherent complexity of such applications and their interactions can bring numerous benefits. A smart city has DT applications in many areas including but not limited to transportation, logistics, power and energy, healthcare etc. The primary goal of DT application in smart cities is to improve the efficiency of systems and thus the sustainability of such systems. For example, from a transport and logistics point of view, the focus is on improving performance in terms of increasing energy consumption and reducing harmful emissions, e.g. Reducing the carbon footprint. Additionally, using DT technologies to predict and remove the bottlenecks between the different elements within a complex system is at the center of communication and health perspectives. The implementation of DT technologies and their integration into management processes is key to improving policy making and decision making in a city. Internet of Things (IoT) creates the connection between all parties, organizations and elements in the smart city with DT technologies. Considering a smart city as a system with so many interrelationships between different components, there are several challenges between the actual components and their DTs. These interactive challenges arise mainly from the presence of a lot of stochastic data with uncertainty. Additionally, there are many challenges related to digital infrastructure, implementation, societal acceptance, regulation and legislation that need to be addressed to enable the integration of DT technologies in smart cities. This complexity surrounding the application of DT technologies in smart cities raises many questions, discussions and solutions that this work aims to address.

Motivation of the Diploma Thesis

The motivation behind this work and its use is to collect remarkable and fundamental concepts related to different applications of DT technologies in smart cities. Discussion of DT applications in smart cities for asset management and the use of technologies such as the Internet of Things, Artificial intelligence and others. To pave the way for the creation of a roadmap for the implementation of DT technologies in Smart Cities by discussing and concluding the benefits, consequences and upcoming challenges of the implementation of DT technologies. Providing guidance, expert recommendations and suggestions to address these challenges. To demonstrate further research on DT technologies and smart cities to ensure safety and reliability. E-governance is a fact that is expanding and will continue to grow as more advanced technology realizes its potential to prevent problems, reduce costs and time, improve efficiency, improve maintenance, facilitate accessibility, encourage new ones innovations and knowledge and even more revealed - goals to be realized. The application of the Digital Twin in this sector is still in its infancy, which means it still has a long way to go to reach its full potential. One more goal for this work is to identify and address the challenges of the Digital Twin in governance.

1.Introduction

Scientific Field Analysis

How to reduce the cost of making a prototype and running tests? How do you run extreme tests on prototypes that aren't possible in a lab? How can a prototype integrate all the information and results from these tests to enable accurate prediction of future behavior? How to monitor a physical asset in real-time and be alerted before something goes critically wrong? How can we humans access this real-time information of all components involved in a physical asset as well as information of the asset as a whole, perform meaningful real-time analysis of this information and make it timely, robust and reliable? How can we make efficient decisions for future operations? The answer is Digital Twin (DT).

Digital twins are virtual copies of a product, process or service that incorporate all of the above properties.[1] Grieves and Vickers define the Digital Twin (DT) as a set of virtual information constructs that fully describe a potential or actual physically manufactured product from the microatomic level to the macrogeometric level.[2] Ideally, all of the information that could be gleaned from inspecting a physically manufactured product can be gleaned from its Digital Twin. DT aim to combine the best of all worlds, namely twinning, simulation, real-time monitoring, analytics and optimization. Digital Twin has been recognized as the next breakthrough in digitization and also as the next wave in simulation.[3] It can save costs, time and resources for prototyping as one does not have to develop the physical prototype(s) but can effectively and accurately perform the same tests on a virtual prototype without affecting real operations. Market Research Future forecasts that the Digital Twin market will reach $35 billion by 2025.[5] Despite the noted benefits and potential of DT technology, there are certain research and implementation gaps that have hampered the adoption and advancement of DT since its inception around 2003.
DT's diverse applicability is a result of its reliance on advanced, evolving technologies, primarily IoT, Big Data, and Machine Learning. The real-time monitoring and data collection capability of a DT relies on real-time data obtained via IoT devices effectively integrated with the environment and/or enterprise information systems, while analysis relies on leveraging available Big Data and Machine Learning tools. Combining these technologies and implementing them on one or more physical assets

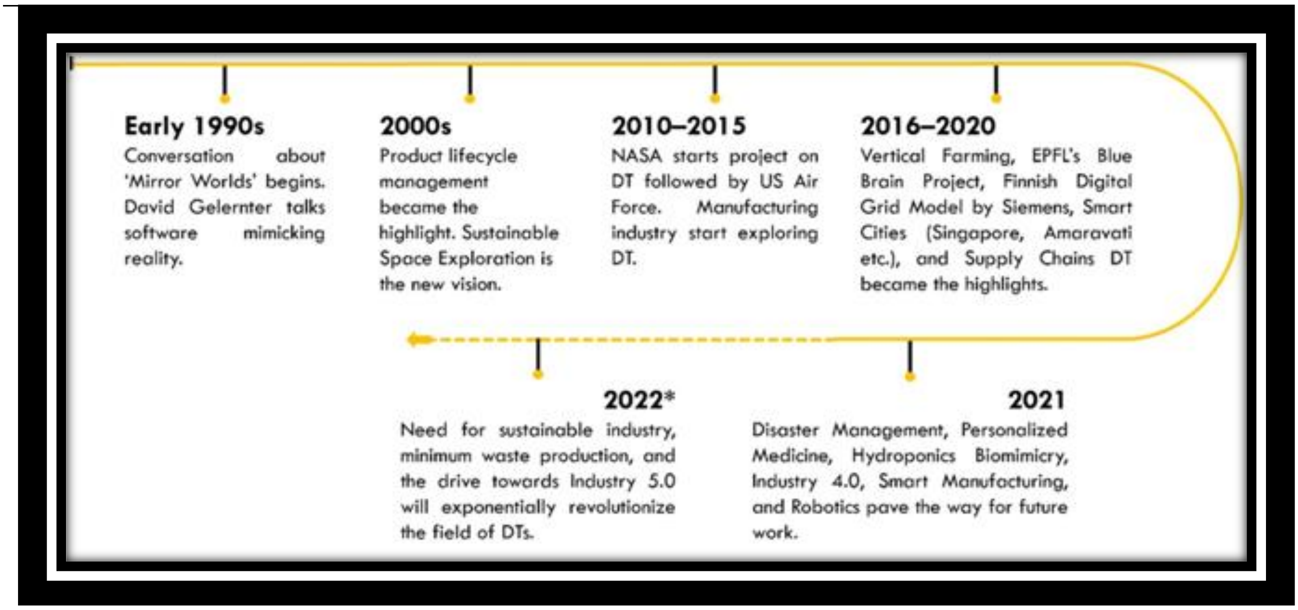
requires extensive domain knowledge, as would be required to create a physical prototype for physical assets. Not only is the overall concept of DT not fully established, there is no universally accepted definition of DT, and there are few early standards for its implementation.[6] As a technology used in different domains and dependent on other evolving technologies, it eventually becomes dependent on the current state of those technologies and also needs to be tailored to each problem and domain.

Digital twin history and evolution

Digital Twin was first introduced by Michael Grieves in a course presentation on Product Lifecycle Management in the early 2000s.[7] In 2011, the implementation of DT was considered a complex process that required many developments in different technologies.[8] Although coined in 2003, the first description of the use of Digital Twins was years later by NASA in Technology Roadmaps where a twin was used to mirror conditions in space and conduct preflight tests.[9] The DT methodology that emerged with the aerospace industry was extended to the manufacturing industry around 2012.

Why did the implementation of the concept take almost a decade?

With the advances in technologies such as Cloud Computing, IoT and Big Data, many fields have experienced major developments, such as Industry 4.0. Industry 4.0 has experienced a revolution primarily through digital advances, IoT and Big Data. Due to Industry 4.0, the storage of all data in digital format and the installation of sensors in industrial rooms, implementations of Digital Twins became possible and rejuvenated the concept. Furthermore, with the emerging rich simulation capabilities and the significant increase in computional resources, it has become possible to conduct realistic tests in a virtual environment.[10] Because of these technological advances, companies like Siemens, General Electric and IBM began implemening a functional DT as a utility for themselves and for their customers.



Early 1990s
Conversation about 'Mirror Worlds' begins. David Gelernter talks software mimicking reality.

2000s
Product lifecycle management became the highlight. Sustainable Space Exploration is the new vision.

2010–2015
NASA starts project on DT followed by US Air Force. Manufacturing industry start exploring DT.

2016–2020
Vertical Farming, EPFL's Blue Brain Project, Finnish Digital Grid Model by Siemens, Smart Cities (Singapore, Amaravati etc.), and Supply Chains DT became the highlights.

2021
Disaster Management, Personalized Medicine, Hydroponics Biomimicry, Industry 4.0, Smart Manufacturing, and Robotics pave the way for future work.

2022*
Need for sustainable industry, minimum waste production, and the drive towards Industry 5.0 will exponentially revolutionize the field of DTs.

Figure 1 Evolution of DT applications

Defining DT

In the simplest words, a Digital Twin is a 'Digital' 'Twin' of an existing physical entity. Although the literal meaning of it seems simple at first glance, the definition of DT has been the subject of debate and development. Below there is a table with the most important definitions of Digital Twins in industry and academia.

Michael Grieves (Academia)	The digital twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro (atomic level) to the macro (geometrical level). At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital twin.
Nasa (Government / Research)	A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.
Cambridge Centre For Digital Built Britain (Academia)	A digital twin is a realistic digital representation of something physical.
Dassault Systèmes (Software)	A digital twin is a near-real-time digital image of a physical object or process that helps optimize business performance.
Gartner (IT)	A digital twin is a digital representation of a real-world entity or system. The implementation of a digital twin is an encapsulated software object or model that mirrors a unique physical object, process, organization, person or other abstraction.

	Data from multiple digital twins can be aggregated for a composite view across a number of real-world entities, such as a power plant or a city and their related processes.
General Electric (Conglomerate)	A digital twin is a living model that drives a business outcome.
IBM (Software)	A digital twin is a virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning and reasoning.
Michael Batty (Academia)	A digital twin is a mirror image of a physical process that is articulated alongside the process in question, usually matching exactly the operation of the physical process which takes place in real-time.
Microsoft (Software)	A digital twin is a virtual model of a process, product, production asset or service. Sensor-enabled and IoT connected machines and devices, combined with machine learning and advanced analytics, can be used to view the device’s state in real-time. When combined with both 2D and 3D design information, a digital twin can visualize the physical world and provide a method to simulate electronic, mechanical and combined system outcomes.
Siemens (Conglomerate)	A digital twin is a virtual representation of a physical product or process, used to understand and predict the physical counterpart’s performance characteristics.
Deloitte (Consulting)	A digital twin is a near-real-time digital image of a physical object or process that helps optimize. business performance.

Table 1 Definitions of Digital Twins across the industry and academia

Components of DT

Grieves first introduced DT with three components: the digital (virtual part), the real physical product and the connection between them.[7] There were other researchers like Tao et al. extended this concept to five components by including data and services as part of DT.[11] Miller et al. extend the definition of DT to an integration of multiple models of a model-based enterprise (by creating associations between different models and relationships between data stored in different parts, a digital twin can be formed).[12] As conceptually sound as above definitions are in order to reach a consensus on a DT definition, it is necessary to specify the basic requirements for a DT. With advances in the technologies that DT relies on (such as Machine Learning, Big Data, and Cybersecurity), these requirements have changed over time. In addition, the domain dependency property of DT requires the definition of components that can be generalized across domains, although their level of involvement and measurement may vary by domain.

The components of DTs defined in two categories. The Elemantary and Imperative components.

Elementary components

The elementary components are those without which a DT cannot exist:

- Physical Asset (Can be either a product or a product lifetime)
- Digital Asset (The virtual component)
- Information flow between the physical and digital asset.

Imperative components

The imperative components complement the features of DT to make it an all-encompassing tool for simulation, real-time monitoring and analysis. Without these, the uniqueness of DT ceases to exist. The existence of each of these components mainly depends on the domain and application of DT.

- IoT devices to collect sensor's information from various sub-components of the physical asset and edge devices.

Requires: High fidelity connection between IoT devices, for accurate and timely information flow.

- Data collected from various IoT components and software. It is required to monitor the system, guarantee correct behavior and provide input to the machine learning system.

Requires: Big data analysis and storage tools to extract useful information from data.

- Machine learning for prediction and feedback, and identifying effective mitigation strategies in exceptional circumstances.

Requires: A common optimization function for the sub-components of the DT.

- Security of the data and information flow between different components involved in the DT.

Requires: Security protocols for information exchange, authentication and authorization mechanisms.

- DT Performance evaluation.

Requires: Evaluation metrics (e.g. accuracy, resilience, robustness, costs), evaluation methods and tests.

Table presents how each component contributes to the different functions of DT.

Component	Role
Physical Asset	What the digital twin is a twin of?
Digital Asset	The digital twin
Continuous Objective Relation	For synchronisation and twinning
IoT	Data collection and information sharing
Data	Synchronisation, analysis and input to Machine Learning
Machine learning	Analytics and prediction
Security	Prevent data leaks and information compromises
Evaluation metrics/Testing	Evaluate the performance of Digital Twin

Table 2 The different components of DT and their key roles.

How is DT different from existing technologies?

The multiple uses of DT such as simulation, real-time monitoring, testing, analytics, prototyping, end-to-end visibility can be broadly classified as subsystems of DT (e.g. a DT can be used for testing during prototyping for real-time monitoring and evaluation or for both). See the table below for a comparison between existing technologies and Digital Twins.

How DT differs from existing technologies	
Technology	**How the technology differs from DT**
Simulation	No real-time twinning
Machine Learning	No twinning
Digital Prototype	No IoT components necessarily
Optimisation	No simulation and real-time tests
Autonomous Systems	No self-learning (learning from its past outcomes) necessarily
Agent-based modelling	No real-time twinning

Table 3 How DT differs from existing technologies

Machine learning in Digital Twins

Machine Learning techniques can be applied to Digital Twins to enhance their capabilities and accuracy. Some ways in which Machine Learning can be used are presented below:

- Predictive maintenance: Machine learning algorithms can analyze sensor data from physical assets and predict when maintenance will be required, allowing for proactive maintenance instead of reactive repairs.

- Anomaly detection: Machine learning can be used to identify anomalies in sensor data from Digital Twins, which can indicate potential problems with physical assets.

- Optimization: Machine learning algorithms can optimize the performance of Digital Twins by analyzing large amounts of data and identifying patterns that can be used to improve system efficiency.

- Simulation: Machine learning can be used to generate more accurate simulations of physical systems by incorporating data from real-world operations.
- Control: Machine learning algorithms can be used to optimize control systems in Digital Twins, improving performance and reducing energy consumption.

Summarizing, Machine learning can significantly enhance the capabilities of Digital Twins, enabling more accurate predictions, better optimization, and improved performance of physical systems.

Big data in Digital Twins

Digital Twins generate and consume vast amounts of data, making Big Data analytics an essential aspect of their operation. Some ways in which Big Data is used in Digital Twins are:

- Data collection: Digital Twins require data from sensors, devices and other sources to accurately represent their physical counterpart. Big data technologies can be used to efficiently collect, store and manage this data.
- Data processing: Big data analytics can be used to process the large amounts of data generated by Digital Twins. This can include filtering, aggregating and cleaning the data to ensure that it is accurate and relevant.
- Predictive analytics: Digital Twins can be used for predictive analysis, using historical data to forecast future events. In addition, can help to identify patterns and trends in this data, enabling more accurate predictions.
- Machine learning: As I previously mentioned, Machine Learning algorithms can be used to enhance the capabilities of Digital Twins. Big data analytics can help to train these algorithms by providing large datasets for training and testing.
- Visualization: Big data analytics can be used to create visualizations of data generated by Digital Twins, allowing users to more easily understand and interpret complex data sets.

Big data analytics is a critical component of Digital Twins. It helps to collect, process, and analyze large amounts of data, enabling more accurate predictions, Machine Learning, and data visualization.

Properties of a Digital Twin

The properties of the DT are what make it more than just a Digital Twin. These are the characteristics inherent in every DT. Below summarized some of the properties:

- Accurate representation: A Digital Twin should accurately represent the physical system or asset that it is modeling. This requires collecting and integrating data from sensors, devices, and other sources to create a detailed and accurate model.
- Real-time monitoring: A Digital Twin should continuously monitor the physical system or asset it represents. This allows for real-time analysis and detection of potential issues or anomalies.
- Predictive analysis: A Digital Twin should be able to predict future behavior or events based on historical data. This can help to identify potential issues before they occur and allow for proactive maintenance and optimization.
- Interoperability: A Digital Twin should be interoperable with other systems and devices. This allows it to communicate with other systems and devices, share data and collaborate with other systems.
- Scalability: A Digital Twin should be scalable to accommodate changes in the physical system or asset it represents. This allows it to grow and evolve along with the physical system, ensuring that it remains an accurate representation over time.
- Security: A Digital Twin should be secure to protect sensitive data and prevent unauthorized access. This requires implementing appropriate security measures such as encryption, access controls and monitoring.

A Digital Twin should be an accurate, real-time and predictive representation of a physical system or asset. It should be interoperable, scalable, and secure to enable collaboration and ensure data protection.

Challenges in DT

While Digital Twins offer numerous benefits, there are also several challenges associated with their implementation and operation. Some of the key challenges are:

- Data integration: Digital twins rely on data from multiple sources and integrating this data can be challenging. This requires identifying relevant data sources, cleaning and processing the data, and ensuring that the data is accurate and up-to-date.

- Data quality: The accuracy and quality of data used in Digital Twins are crucial to their success. Low-quality data can lead to inaccurate predictions and poor performance.

- Complexity: Digital Twins can be complex, requiring expertise in multiple domains such as engineering, data analytics and software development. This can make it challenging to find the right skills and expertise to develop and operate Digital Twins.

- Scalability: Digital Twins can generate large amounts of data and scaling the system to accommodate this data can be challenging. This requires appropriate infrastructure, data storage and processing capabilities.

- Security and privacy: Digital Twins can contain sensitive data and ensuring the security and privacy of this data is crucial. This requires implementing appropriate security measures and ensuring that data is accessed only by authorized individuals.

- Interoperability: Digital Twins may need to interact with other systems and ensuring interoperability can be demanding. This requires developing appropriate interfaces and protocols to enable communication and collaboration with other systems.

Digital twins offer significant benefits, but their implementation and operation can be challenging. Overcoming these challenges requires expertise in multiple domains, careful planning and effective management.

The gap between the ideal DT and practical DT

There can be a gap between the ideal Digital Twin and the practical Digital Twin, where the practical one may not fully realize the potential benefits of the ideal. Here are some of the key factors that contribute to this gap:

- Data availability: The ideal Digital Twin requires high-quality data from various sources, but in practice, this data may not be available or may be difficult to obtain. This can limit the accuracy and predictive power of the Digital Twin.
- Data quality: Even when data is available, its quality may not be adequate for use in a Digital Twin. Incomplete or inaccurate data can limit the effectiveness of the DT.
- Technical limitations: The ideal Digital Twin may require advanced technologies such as Artificial Intelligence and Machine Learning, which may not be practical or feasible for all organizations. Technical limitations can limit the effectiveness of the DT.
- Cost: The ideal Digital Twin may require significant investments in hardware, software, and expertise, which may not be practical for all organizations. Cost considerations can limit the scope and value of the DT.
- Implementation challenges: Implementing a Digital Twin can be demanding, requiring expertise in multiple domains, careful planning, and effective management. Implementation difficulties can limit the succession of the DT.

While the ideal Digital Twin offers significant benefits, the practical one may not fully realize these benefits due to limitations in data availability, data quality, technical limitations, cost and implementation challenges. To bridge this gap, organizations should carefully consider the benefits and limitations of Digital Twins, identify the most critical areas for improvement and invest in the necessary resources to maximize their effectiveness.

Conclusions of chapter and future steps

Digital Twins are virtual representations of physical systems or processes that enable real-time monitoring, analysis and optimization. In addition have great capabilities combining real-time modelling, simulation, autonomy, agent-based modelling, machine learning, prototyping, optimisation and big data into one. One of the main advantages of DTs is their ability to simulate the behavior of a physical system or process in a virtual environment, allowing engineers and operators to identify and address potential issues before they occur. This can reduce downtime, improve efficiency and increase productivity. Digital Twins can also facilitate collaboration among different stakeholders, including designers, engineers and operators, by providing a shared platform for data analysis and decision-making. Additionally, they can help organizations optimize their resources, reduce costs and improve customer satisfaction. However, creating and maintaining a Digital Twin requires significant investment in technology, infrastructure and expertise. It also raises important ethical and security concerns related to data privacy, ownership and cybersecurity. Digital Twins have the potential to revolutionize how we design, operate and maintain physical systems and processes. Their benefits are likely to outweigh the costs, especially in industries where reliability and efficiency are critical.

As Digital Twin technology continues to evolve, there are several future steps that can be taken to further improve and enhance their capabilities. Here are some of the key future steps:

- Incorporate more advanced technologies: Digital Twins can be enhanced by incorporating more advanced technologies such as Artificial Intelligence, Machine Learning and Blockchain. These technologies can enable more sophisticated data analysis and improve the accuracy and predictive power of DTs.
- Enable cross-domain integration: Digital Twins can be extended to integrate multiple domains, enabling greater interoperability and collaboration between different systems and devices. This can enhance the overall efficiency and effectiveness of Digital Twin applications.
- Improve data quality: Digital Twins rely on high-quality data and future steps can be taken to improve the quality and accuracy of the data used in implementation of them. This includes

integrating data from multiple sources and using advanced data processing techniques to improve the accuracy of the data.

- Enhance security and privacy: Digital Twins contain sensitive data and future steps can be taken to enhance the security and privacy of this data. This includes implementing appropriate security measures such as encryption and access controls and ensuring that data is accessed only by authorized individuals.
- Enhance visualization and user interface: Digital Twins can be made more user-friendly by enhancing their visualization capabilities and user interface. This can improve the usability of Digital Twin applications and enable greater collaboration between different stakeholders.

In conclusion, Digital twin technology offers significant potential for improving the efficiency and effectiveness of a wide range of systems and processes. Future steps can be taken to further enhance the capabilities of Digital Twins, enabling organizations to maximize the benefits of this technology.

2. Key sectors for Digital Twins

This chapter focuses on the applications of Digital Twins. First starts by looking at the applications for Digital Twins, discussing the domains and specific problems. In this time period the implementations of Digital Twins are growing in daily base with the advancements of IoT and Artificial Intelligence (AI) allowing this growth to increase more quickly. At this stage, the primary areas of interest are Manufacturing, Automobile, Aerospace, Healthcare, Smart Cities, Governance etc.

The aim of this chapter is to identify and understand the potential of DTs in each sector but also why must be to implemented, which may prove beneficial to any researcher, company, city, goverment etc. to unlock the true power of the Technology.

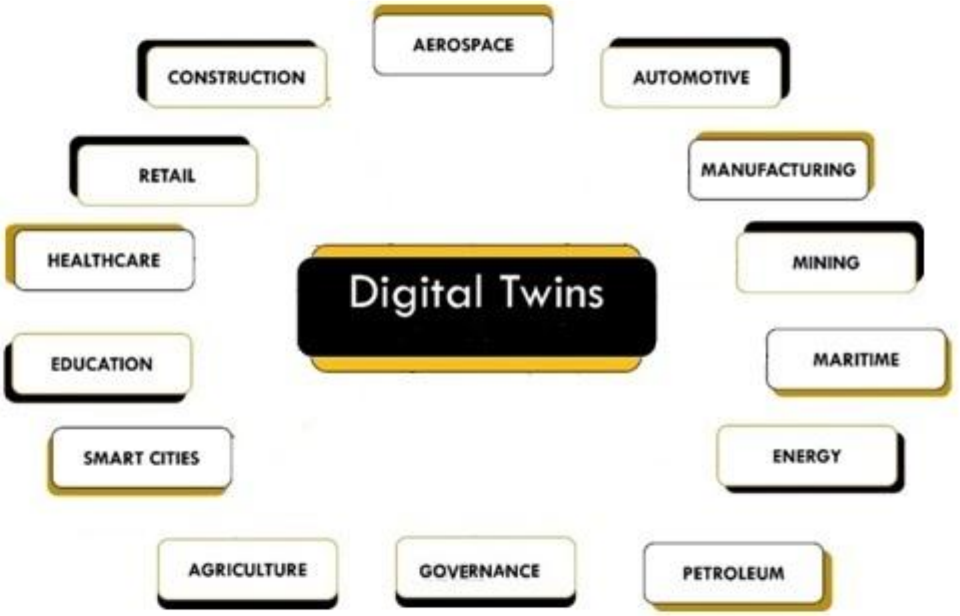


Figure 2 Different industrial sectors where DT has found its applications

Aerospace &Aeronautics

Aerospace and Aeronautics sectors were the pioneering areas where DT was first explored by NASA and the US Air Force. The main applications of DTs include optimizing spacecraft and aircraft performance and reliability, predicting and solving maintenance problems and increasing the safety of missions for the crew.[19] The main application of DT began with the intention of optimizing spacecraft or aircraft performance and reliability. According to NASA, the uses of DT for them were:

- ✓ Flight simulation before actual vehicle launch to maximize mission success.
- ✓ Mirroring actual flight and updating conditions such as actual cargo, temperature and other environmental components to predict future scenarios.
- ✓ Diagnosing damages on the vehicle.

- ✓ Providing a platform to study the impact of changing parameters not considered during the design phase.

Any damage found by DT could be remedied by enabling on-site repairs or recommending appropriate changes to the mission, resulting in longer mission life and higher success rate. By reducing the uncertainty of forecasts and maintenance intervals, DT improves the planning and reliability of future missions. In addition, to securing the spacecraft and mission, DT has also been used to ensure the safety of crew members operating in remote and unfamiliar areas by testing various possible emergency recovery scenarios. [9][20]

Performance and reliability aside, one of the benefits of using DT is that it can be used to predict failures, making spacecraft or aircraft maintenance easier and cheaper than traditional planned maintenance. The US Air Force Research Laboratory (AFRL) announced that it will create a DT of one of its supersonic bombers called the B-1B for predictive maintenance, which will performe by 3D scanning every single part of the aircraft, right down to the nuts and screws. The scanning process will uncover any structural flaws or damage, which will aid in the creation of a medical record. Then the plane's data will predict areas where structural problems are more likely to occur. Over the aircraft's life cycle, layers of maintenance data, test/inspection results and analysis tools are overlaid on the digital model. AFRL has signed a $20 million contract with Northrop Grumman to develop a DT to predict the airframe problems of various types of Air Force aircrafts so that preventive maintenance can be performed. Their experts try to improve predictive maintenance for the aircraft by improving flight load data, developing more realistic structural analysis models, and quantifying and reducing model uncertainty. The lifespan of an aircraft is highly dependent on the load it carries. The life of an aircraft can be increased by up to 200% with a weight saving of only 20%. With the help of DT technology, the load profile of an aircraft can be recorded and processed to determine its useful life.[21]

A DT for fan-blade reconditioning has been proposed by Jonh Oyekan and his team[22], which involves the use of cameras and visual algorithms along with a robotic arm to grind aircraft engine fan blades to the required specification for improved maintenance, repair and overhaul in aerospace and space travel. Another researcher, Shimin Liu and his team[23], proposed a DT for aircraft rudder machining processes that can mimic physical machining processes in three aspects: geometry, behavior and context. NASA even developed the rocket engine's DT to better predict real-world flight conditions and their impact on engine launch. [24]

DT enables the aerospace sector to develop new procedures faster and more cost-effectively, while improving production line quality and reducing aircraft maintenance time. New player in the aerospace industry, SpaceX, also uses DT technology for product design and testing to address the issues and get the required performance before they even build the products, which allows them to build cheaper rockets develop.

The introduction of a DT in the aerospace industry is highly beneficial, although it can be a slow process due to aircraft regulations and data collection mechanisms, making it expensive, as well as there are certification concerns for onboard equipment and software.[25]

Manufacturing

Although DT's development began in the Aerospace, the sector exploring the technology the most is Manufacturing. Digital Twin Technology have been described as key enabler of Industry 4.0 and Smart Manufacturing. Every manufactured product goes through four main phases during its life cycle: Design, Manufacture, Operation and Disposal. Smart manufacturers can use DTs in all four phases of the product. [26]

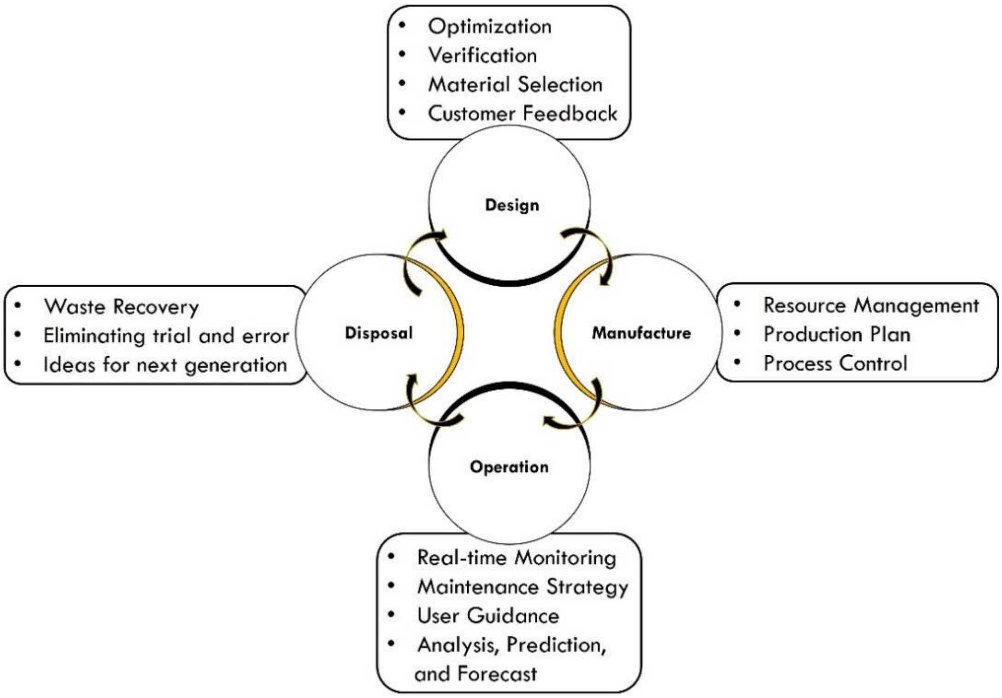


Figure 3 DT's applications throughout a product's lifecycle
Source: Izabela Rojek et al (2021) Digital Twins in Product Lifecycle for Sustainability in Manufacturing and Maintenance

During the design phase, DT allows designers to virtually review their product design, allowing them to test different iterations of the product and choose the best one. Using real-time data from previous generation products, designers can gain insight into the features that work best for consumers and those that need improvement. This makes the whole process of improving the design easier and faster. An example of this is the car manufacturer Maserati, which used DT virtually to optimize body aerodynamics with otherwise complex and expensive wind tunnel tests. They also optimized the car's interior acoustics using data from a microphone-equipped dummy in the prototype car. With customer reviews, designers can better understand the needs, which can be translated into better features. Capturing customer preferences via a DT informs companies of market trends, which can be integrated with customer usage data to see the impact on product performance. This allows companies to make design decisions and integrate them in an informed manner, simplifying the process of incorporating customer feedback into the product to deliver customized products. In addition, a DT can help designers choose the material for their products. Converting raw materials into a finished product is the next step in manufacturing. A DT can be a useful tool in resource management, production planning and process control at this stage. A DT can be helpful in (i) production planning and control through automatic planning and execution of the orders and improvement of decision support through detailed diagnostics, (ii) Maintenance through evaluation and analysis of machine conditions, detection of changes in the production system and of their effects with predictive maintenance and (iii) Layout planning through continuous evaluation of the production system. By predicting failures, DT reduces downtime by allowing either maintenance work to be scheduled or preventive action to be taken. According to Fei Tao and his team [27] a DT can provide nine types of product services which includes the service of (i) Real-time monitoring, (ii) Energy consumption analysis and forecast, (iii) User management and behavior analysis, (iv) User operation guides, (v) Intelligent optimization and updates, (vi) Product failure analysis and prediction, (vii) Product maintenance strategy, (viii) Product virtual maintenance and (ix) Product virtual operation.

Therefore, the information that could improve the next generation product/system is often lost when the product is retired. In addition, to improving the manufacturing process through different stages of a product, a DT also offers advantages for the field of Additive Manufacturing. [28] Creating a DT of a 3D printing machine can help achieve a product with the desired characteristics by eliminating the need for multiple iterations of trial and error testing, which in turn shortens the time between design and production, and thus the overall additive manufacturing enables process time and be cost-effective. One of the most developed directions in manufacturing, especially within the framework of Industry 4.0, is robotization and automation of production lines. DT plays a critical role in this integration, as industrial robots are programmed using methods that are closely related to twinning of manufacturing equipment.[29]

DTs in the manufacturing industry are beneficial to future products even before the actual product exists. It helps with development, testing, process optimization, preventative maintenance, product services and proper disposal. By detecting design flaws early, DT-based intelligent manufacturing systems can reduce the time and cost of physical reconfiguration. In addition, DT contributes to better visualization, which contributes to better learning and decision-making and collaboration by providing access to a broader group of professionals to collaborate. In this way, DTs lead to a better understanding of equipment and processes by everyone, resulting in better designed products and more efficient time and resource saving processes, while ensuring that there is a strong and fluid connection between the different phases of the Manufacturing. [30]

Healthcare and Medicine

Healthcare is one of the largest industries in the world and its integration into daily life is ubiquitous.

DT healthcare technology addresses the hospitals, operational strategies, capacity, staffing and care models to optimize care, costs and performance of the healthcare sector and assists in informed and strategic decision making. Besides to facilities and infrastructure improvements, it also has applications to simulate patient behavior to provide them with tailored healing and care.

Siemens designed a DT for the radiology department of a hospital in Dublin, Ireland, which was facing challenges in delivering efficient patient care and experience due to increasing patient demand, escalating clinical complexity, aging infrastructure, lack of space and prolonged wait times, disruptions and delays. Siemens, together with the hospital, redesigned the department's layout and tested new operational scenarios by creating a 3D computer model of the radiology department and its operations, and then applying process optimization using workflow simulation. To gain better insight into the department, they conducted a week-long on-site assessment that included workshops, stakeholder interviews and process observations. Within weeks of implementing the DT, significant improvement was seen, resulting in reduced wait times, faster patient turnaround time, better equipment utilization, and reduced staffing costs.[31]

It is now possible to exist tailored treatments for the patients, as one disease is diversified based on socioeconomic and geographic background, genetic makeup, gender, age group, family history and lifestyle choices. This is also referred as personalized medicine. DT technology fits neatly into the field of precision medicine as DT results are fully dependent on the input data (Figure). For personalized treatments, a DT can be designed for the whole human body, for a single body organ, for finer body component levels, for a specific disease or disorder etc.

Despite this, unlike other industries, it is difficult to establish a connection between humans and their DT because humans cannot be embedded with sensors. However, once human DT is developed, it will be able to suggest the right treatment for the patient based on its data.

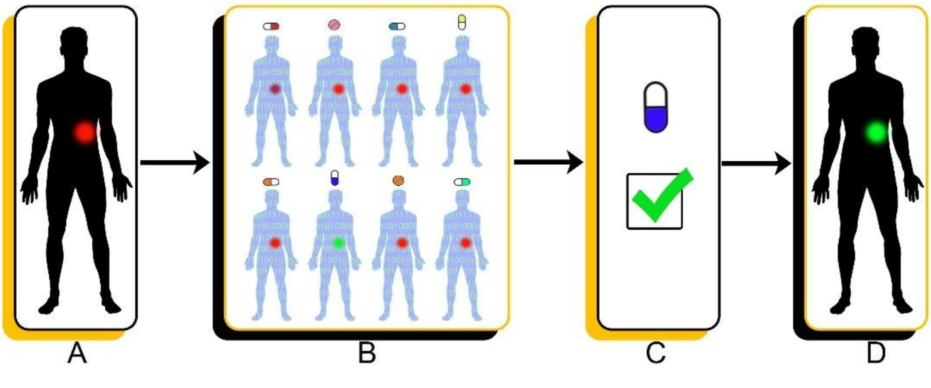


Figure 4 DT concept for personalized medicine
Source: Bergthor Bjornsson et al (2019) Digital twins to personalize medicine

(A) A patient with a local sign of disease (red). (B) Patient’s DT is created and virtually treated with different treatments/medicines in various combinations. (C) Treatment showing the best results is chosen. (D) Personalized medicine is given to the patient to treat them (green).

Even though human DT seems like an innovative dream, digital models of organs and body parts have been already created. The Hewlett Packard Enterprise (HPE) [32] launched the Blue Brain Project to reconstruct and simulate a digital brain model to understand complexity and brain disorders at different levels. Philips also has developed Heart Model. In this project, the patient's data and a generic heart model are combined to create a personalized 3D model of the heart for early detection and prediction of cardiovascular diseases. Another company, which is working on developing a DT of the human heart is Siemens. They have been successful in simulating the physiological processes of a heart using electrocardiograms measurements which were used to predict results of the treatments for the selection of the one with the most chances of success.[33]

The United States Food and Drug Administration authority is also considering DTs as a potential clinical trial tool to accelerate medical innovation along with regulatory approvals. They collected data from a number of historical clinical trials on Alzheimer's disease and used it to train a machine learning model to generate a DT to predict disease progression, and found that the DTs were not statistically different from actual subjects in the control group. Digital Twins technology is emerging as an exciting tool in the healthcare sector that looks promising for the future. From one point of view, DTs of healthcare infrastructures, such as hospitals, regional health centres and medical staff, can optimize patient care, costs and performance. On the other side DTs of patients can be a step towards personalized treatment and medicines. Both types of applications of DTs in the healthcare will improve patient experience and treatment success. However, there are some concerns to certification and regulation issues, as well as security and privacy when implementing the technology.[34]

Power Generation/Energy

Companies involved in the generation and sale of energy from non-renewable resources such as oil, gas and nuclear power, or from renewable resources such as wind, solar, and hydroelectric power fall under the energy sector. The DT technology in the energy sector is being used from nuclear plants to wind farms. General Electric (GE) successfuly created a DT of an entire wind farm. The DT of a wind turbine increases its energy production, optimizes its maintenance strategies and improves its reliability by collecting real-time data such as weather, service and performance reports, among other things. GE offers its customers comprehensive hardware and software solutions for creating, expanding and optimizing their wind farms using their cloud-based software DT platform called Predix. [35] Likewise, DNV, a company that provides testing, certification and consulting services for the energy and renewable industries, has developed a DT analysis tool called WindGEMINI for wind turbines that helps improve wind farm performance through predictive maintenance. [35] A DT of wind turbines can be used to design and test them and find the best position to maximize energy production by considering factors such as wind speed, waves, temperature, etc.

The prediction and query capabilities of DTs will be leveraged for the next generation of power grids.

Siemens has developed DTs for the planning, operation and maintenance of the Finnish power grid by creating a single digital grid. In addition to improved safety and reliability, the benefits include: (i) resource savings by converting most of the manual work into automated work for simulations, (ii) efficient and improved use of data, (iii) easier use of data for new applications and (iv) improved decision-making using Big Data. Finland and Norway plan to deploy a DT to optimize power grid operations with the new complexities introduced by intermittent renewable energy and decentralized energy resources. The DT will enable operators to predict grid conditions, balance grids and prevent blackouts. [36]

Moreover, DT technology, when applied to nuclear power plants can improve the algorithms used to control and test the plant and perform diagnostics on plant equipment such as pumps, motors, valves, etc. One of the main uses of these DTs will be training new operators and engineering students. Unlike in the real world, the DTs of these nuclear power plants will make it possible to completely virtually access in a working reactor, with analysis all the kind of information about the behavior of it.[37][38]

As the demand for renewable energy sources increases, so does the demand for their DTs, which can be used for their optimal design, maintenance and performance, and for power distribution. According to Siemens, implementing DT is a prerequisite if we are to save the planet from the damaging effects of climate change. The DT can play a critical role in optimizing power generation and distribution, as well as maintaining the assets involved in power generation.[39]

Automotive

As in other sectors, predictive maintenance is one of the applications of a DT in automotive. Automotive also uses DT technology to offer its customers more personalized services by collecting and analyzing behavioral and operational data of the vehicle.[40] This allows automakers to build a car that meets their customers' needs by tracking features as a function of their usage. It is believed that except from monitoring and predictive maintenance of vehicle services and parts, a DT can also boost vehicle sales. A DT can provide a 360-degree view of the vehicle and integrate customer preferences, which combined with AR can facilitate the overall sales experience by making it more immersive and interactive.

Tesla Inc. is developing a DT for every car that manufactures. By using data from individual vehicles, the company ensures that each of its cars is performing as intended. With the data, Tesla also updates the software for each car individually and then uploads it to fix several maintenance issues, such as the compensating for a rattling door by adjusting the hydraulics. Another automotive company using DTs is Volkswagen. This company used DTs to integrate a new robotic workstation at one of its manufacturing facilities. They created a highly detailed 3D model of their facility that included robotic arms, sensor logic and safety components, then simulated processes and procedures before adding the production line. Maserati also used a DT to add two new assembly lines to an existing facility. They saw how the car design changes would affect production with a DT and then adjusted the production processes accordingly.[42]

A DT has even found its way into competitive sports such as Formula 1 (F1) racing. The Mercedes team has developed a digital twin to analyze the performance of its car after each race. A total of 150 sensors in the car collect data every 0.001 seconds on temperature, pressure, acceleration, forces, shaft speed, etc., which is supplemented by virtual sensing, so that data sets have to be processed by the end of the races. With the help of a DT, the race engineers study the data to build a car that performs better and offers greater reliability and safety. All data from the race will help the team develop strategies for future races. In addition, F1 drivers are now using the simulations to prepare for the real races, test new design features and gain a deeper understanding of vehicle behavior.[43]

Another area in the automotive sector where DTs find application is in autonomous vehicles. Each autonomous vehicle is validated for safety and motion algorithm aspects in commercial or digital open source environments. Because most vehicles are unique in their development and manufacturing process, manufacturers work to connect every single aspect of the vehicles.[44]

DTs in the automotive can benefit manufacturers in their manufacturing process, as well as car dealers in sales by providing a more interactive and immersive customer experience. Not only that, but it can also give the customer the option to customize their vehicles to their liking. DTs bring value to every user and it doesn't matter if it's a regular rider or a competitive rider.

Oil and Gas

The oil and gas sector generates approximately $3.3 trillion in revenue annually, making it one of the largest sectors in the world in terms of monetary value. The advent of DT technology in the oil and gas industry has brought tremendous value to this industry by being a powerful tool to (i) reduce and better understand risk, (ii) create and manage executable work schedules, and (iii) identify risks to changes in the process and respond accordingly. Additionally, DT can be a crucial resource for oil companies when it comes to extracting offshore resources.[45]

BP (British Petroleum), one of the largest oil and gas companies in the world, uses DTs for several of its North Sea assets called APEX. APEX helps in safely optimize production, remote monitoring, preventive maintenance, save time in optimization and testing. The most notable benefit of DTs for BP was an increase in oil and gas production by 30,000 additional barrels per day worldwide.[46]

Another oil and gas company using DT technology is Royal Dutch Shell. Collecting more than 10 million operating data per minute, they use them to maintain, improve productivity, safety and reduce emissions by anticipating the conditions to optimize plant performance and managing them autonomously. They also developed an improved fatigue model for their assets using the DT concept, combining data from sensors with a structural finite element model to accurately predict asset life so they can manage inspection planning and safety incidents. Other companies are also using the technology to maximize productivity while minimizing costs and risks.[47][48]

As the oil and gas industry relies on heavy and demanding equipment and machinery located in remote areas under extreme environmental conditions, a DT makes the monitoring and control of the activities safer, thereby reducing the associated risks. In addition, by predicting downtime, DT improves the overall process, which translates directly into time and cost savings.

Mining

The mining sector, dedicated to locating and extracting metal and mineral deposits from the earth's surface is considered to be one of the oldest established industries. Just as the oil and gas industry, a DT is a perfect tool for optimizing operations at mining sites. Ernst and Young has identified DT as one of the key enabling technologies in the mining industry as it moves through digitalization.[49] In their report, they identified four areas where DTs contribute to mining: (i) Mine operations: predictive maintenance improves asset reliability and reduces unplanned downtime (ii) Processing: optimization of asset setpoints improves process efficiency and product quality, and reduces Bottlenecks (iii) Transportation: Predicting and optimizing the transportation network improves transportation reliability and (iv) End-to-End: Simulation and analysis of different scenarios along the value chain determine optimal plans and schedules. Additionally, DTs help the miners to test new processes or machines before using the real ones onsite and also train new miners especially for emergency situations by educating them on the right procedure and training them remotely in a risk-free and stress-free environment.

PETRA DataScience [50] a provider of value chain digital optimization software, has developed the world's first DT for mine value chain optimization. Their machine learning DT uses two years of historical data to simulate mine planning, blasting, metallurgy, and process control options. Company Gold Silver Mine used the DT in Laos, which used rock type data to optimize crushing efficiency during drilling and blasting, thereby increasing the rate of metal recovery from the mine.[51]

Anglo American PLC [52] a global mining company, uses the DT at its mining sites in Chile and Brazil to reduce the fuel consumption of its trucks, thereby optimizing the mining fleet. By tracking the performance of the transportation fleet, they can analyze the data used to improve equipment efficiency, condition monitoring and predictive maintenance. They also plan to implement DT for their pipelines, smelters and refineries to make the process more effective and efficient. Rio Tinto [53] the second largest metals and mining company in the world also uses DT at the Gudai-Darri mine located in Pilbara Australia. With the use of the DT, they can safely test new ways to improve their productivity without damaging parts or stopping processes within the plant.

DT Technology has the potential to add new value to the mining industry, from increasing efficiency to creating a safer environment, which explains why mining companies are investing in DT Technology. A global provider of market intelligence and consulting services International Data

Corporation (IDC), has forecast that 70% of mining companies will invest in DT technology over the next few years.

Maritime and Shipping

Activities related to the ocean, the sea, ships, navigating ships from one destination to another, seafarers, etc. is represented by the maritime and shipping. This sector also includes the transportation of passengers in sea. Globally, around 80% of trade volume and 70% of value is carried by sea, which is the primary mode of transport for goods according to the United Nations (UN). Similar to the aerospace industry, the primary application of DT focuses on increasing equipment reliability, improving maintenance and reducing operating costs.[54]

The United States Navy and Department of Defense are building a DT for their ammunition cargo ships with help from General Electric. Data collected from ship equipment such as variable frequency drives, propulsion motors, diesel engines and generators is used to compare the ship's real-time performance with performance variations. Possible failures in the engines or other critical infrastructure are reported and rectified before they even happen. In this way they improve the availability, efficiency, operation and readiness of their resources and missions. The DT also enables remote monitoring and diagnostics. [55]

In 2019, DNV, creator of the aforementioned WindGEMINI which has been referred in energy sector, implemented DT technology on one of the largest crane vessels in the world. The ship requires constant inspections due to its large capacity of 14,000 tons, which puts it under high stress. The DT facilitates reporting, issue assessment, maintenance planning and predictive analysis, resulting in huge cost savings. DNV believes DT can bring significant benefits to all stakeholders in the maritime industry, including shipowners, equipment manufacturers, government agencies, universities and maritime academies. [56]

DT technology is not only limited to ships/vessels, but is also finding its way into ports. The port of Rotterdam [57] has sensors in its docks that collect real-time data of the environment and water conditions, including air temperature, wind speed, humidity, turbidity, water salinity, current, level, tides and currents. The harbor even features Digital Dolphins, smart quays and sensor-equipped buoys. In addition, they have a physical container, Container 42, equipped with a sensor that uses AI to optimize the ship's travel time and multiple cargoes to be transported.

Agriculture

Agricultural sector companies are involved in the harvesting and production of agricultural commodities such as grains, livestock, poultry, fish, as well as fertilizers, packaged foods, and agricultural machinery, etc. With the growing human population, agriculture is under extreme pressure to increase production to meet the nutritional needs of this record number of people. The Food and

Agriculture Organization of the United Nations reports that in the next 30 years the population of the earth will be 10 billion, creating demand for food, feed and biofuels higher than now. To reach this productivity goal, people need access to all available tools. Developing a DT for smart farming can enable sustainable development and increase food security for the world population.[58] Even if DT technology is still at an early stage of development in agriculture, potential applications in this area have been identified.

Verdouw and Kruize [59] presented potential applications of DTs in different areas of agriculture at the Asian-Australasian Conference on Precision Agriculture, such as: animal husbandry, beekeeping, plant storage, agricultural machinery, etc.

- ❖ Remotely monitoring livestock to detect and analyse their health including heat and estrus cycles and also tracking animals' movements.
- ❖ Identification of pests or diseases in plants.
- ❖ Management and optimization of production plants and replenishment routes by monitoring the stocks of the cereals.
- ❖ Assessment the cost-effectiveness of crop management treatments along with real-time machine tracking.
- ❖ Detection and identification of flies in olive farms to use pesticides effectively
- ❖ Monitoring bee colonies for diseases and managing honey storage.

J. Monteiro et al. [60] presented a reference model for the implementation of a DT in vertical farming by enriching the physical system with sensors that collect data on temperature, humidity, luminosity and the relative CO^2 concentration, which are stored in the cloud. Using intelligent data analysis, the system will be able to suggest methods to plan vertical farms and increase production.

In addition to managing livestock and farms, DT can promote sustainability. Agriculture uses 11% of the world's land area and 70% of its freshwater, and is also responsible for 80% of deforestation. DT Technology can help by tracking any changes related to carbon emissions, biodiversity, pollination and water use management.

Education

Education is an interesting sector where DTs has started to find its applications, particularly in technical courses where the systems are complex and hands-on training on those systems is an essential part. A DT is a great tool for communication in education as it represents multiple domains and visualizes the performance of systems and subsystems, leading to a better understanding of systems and thus simplifying and accelerating knowledge sharing across a range of technological disciplines.[61] DT technology can enhance learning and motivate students to study. The benefits of using DT for learning include:

- ❖ Authentic learning experiences which promote effective knowledge in construction, skill mastery, learning transfer and self-efficacy.

- Learning about the physical twin behavior in the real world under different operating conditions.
- Get instant feedback on system behavior, leading to problem identification and resolution.
- Inquiry-based learning during system development and testing.
- Each student can work on an individual DT, unlike the case where students had to share limited resources.
- DT is a great tool for remote students who don't have access to a physical twin.
- DT ensures student and equipment safety.

In the Skoltech private institute which is located in Moscow, a module focused on developing a DT for designing, prototyping and testing complex systems, in their case an unmanned aerial vehicle (drone), was introduced for master's students. Similarly, the University of Southern California has also proposed an educational DT testbed for engineering students that can enhance their learning experience by allowing them to explore the complexity and behavior of physical systems through interaction with their DTs. [62] As the demand for DTs will accelerate across multiple industries, so will the demand for skilled engineers and technicians. In the future, we can expect more courses to be introduced at colleges and universities that focus on DTs.

Construction

The construction sector demands labour and time. From planning to decommission, a lot of data is generated during the entire life cycle of a project. Therefore, each step or phase of the project lifecycle requires proper communication and information flow between the different stakeholders involved, such as the architects, engineers, contractors, facility manager and workers. This can be achieved by using DTs. Just like in manufacturing, BM can also be used in construction in different life cycle phases of construction projects: the planning and engineering phase, the construction phase, the operation and maintenance phase and the demolition and restoration phase. [63] The table below lists all actual and potential uses of DTs in all phases of a construction project.

Phase	DT Applications
Planning and Engineering	• Helps in building information modeling. • Reduces overall design process. • Minimizes the possibility of incurring additional costs during rework. • Helps in problem-solving by allowing data to be added, modified and verified against real-life scenarios. • Allows collected data to be used by designers for future projects. • Improves decision-making regarding feasibility of project, material selection, energy analysis and management, procurement, supplier selection, sustainability issues, etc.

Construction	• Assesses the structural system integrity. • Ensures building does not fail when forces are applied to it. • Promotes modular construction activities. • Prepares as-built drawings when the design drawings are not available. • Assists in managing resources, materials, schedule, quality, sequence, etc.
Operation and Maintenance	• Monitors the condition of building assets continuously. • Optimizes maintenance and services in the building • Aids predictive maintenance and ensures well-informed decision making. • Monitors logistics processes • Simulates building energy consumption.
Demolition and Restoration	• Helps in problem solving by using data from the predecessor for the next generation buildings having similar characteristics. • Conserves and preserves heritage assets virtually that need demolition. • Identifies potential hazards, technical solutions, possible actions to be undertaken regarding the conservation of their assets.

Table 4 Actual and potential applications of DTs in different phases of construction

One of the greatest benefits of using DTs in the construction sector lies in Building Information Modeling (BIM), a system that generates and maintains information about a construction project throughout its lifecycle. BIM is still mainly used to improve resource efficiency and knowledge sharing during the design and construction phases to facilitate the tasks of the construction stakeholders and avoid costly design errors that are easier to achieve with DTs.[64] In addition, DTs encourage the inclusion of sustainability early in the design phase. Using a DT, the carbon footprint and energy consumption of each building can be estimated in advance, which can be taken into account during design and construction. From the planning to the operational phase, a DT can be a valuable tool in the construction sector. With a DT, it becomes easier to keep track of all the changes and see the impact of those changes. The application of a DT has the potential to transform the sector of construction. So stakeholders have to be open to change and take advantage of the opportunities that come with it.

Retail

Retailing includes all shops and stores that sell the products or goods directly to the consumer. The success of any retail business depends on its customer base. It is not enough to acquire new customers but it is equally important to retain the existing customers by providing the best of support. DT technology in retail offers great potential in terms of consumer experience and marketing. By creating a customer DT, retail stores can offer a unique and tailored customer experience based on customers' interest patterns. Customer satisfaction can be further increased by providing them with relevant suggestions based on their DT without irritating them with multiple recommendations. DT technology enables retailers to transform their products into a dynamic platform that continuously collects data about customer needs and purchasing behavior in order to offer them better products and services. Combining the data from a customer DT with Machine Learning to understand customer behavior will be beneficial for both customers and retailers.[65]

Another benefit retailers can derive from DT technology is in their logistics and supply chain. DT can be used to track and trace the products within the supply chain for more efficient and reliable inventory planning, aggregated planning and demand forecasting. A supermarket chain called Intermarch which is located in France, created a DT of with user data from IoT-enabled shelves and sales systems to get real-time inventory details and test the effectiveness of different store layouts before implementing them.[66] Due to supply chain disruptions caused by the COVID-19 pandemic, 82% of retailers are changing the way it is managed and as such are using DTs as a tool to counteract this. DTs provide real-time monitoring that can enable retailers to implement new, non-linear supply chain fulfillment models that are more efficient. Additionally, during emergencies or disruptions such as the COVID-19 pandemic, DTs can be used to simulate various what-if scenarios in the digital world before decisions are made in the real world. The pioneer companies in developing a DT of their supply chains are BMW and 3M.[67]

The implementation of DTs in retail is relatively new compared to other sectors, but the benefits are multiple, mainly in stores and supply chains. Given the above benefits, increased retail adoption of DTs is expected in the next years.

Smart City

A smart city is the one that uses information and communication technology to run it efficiently by collecting, analyzing and integrating the key information of core systems, thus making intelligent decisions for the needs of the city, including livelihood, environment, public safety, urban services etc. In smart cities, DTs have also found their application in urban planning to improve people's quality of life.[68] A significant example is Carson City in Nevada of USA. The Carson City Public Works Department developed a DT to manage its water supply, resulting in efficient water service for 50,000 city residents and a 15% reduction in operating hours. Using a DT for planning and decision making can result in cities that are more economically, environmentally and socially sustainable.[69] Singapore's National Research Foundation (NRF) has created a virtual Singapore combining 3D maps, city models and a data platform with details such as building materials, components of facilities, etc. NRF believes that Virtual Singapore will not only benefit the government but also its citizens, business owners by acting as a testing ground for new ideas and providing information to aid in decision-making, resource planning and will help administration. It can also be used to improve accessibility of a specific area and simulate emergency situations.[70] Another city to be added to this list is Amaravati of India. The city's DT will be designed for a population of 3.5 million people and will cost \$6.5 billion. The project will cover an area of 217 km^2, which includes 134 km of subway network, 316 km of main roads, over 100 hospitals and schools, 40 colleges, 3 universities and 3 state government buildings. According to Cityzenith, the company responsible for developing the city's DT, when completed, Amaravati will be one of the top three digitally advanced cities in the world. Having cities on digital platforms will allow their stakeholders to monitor real-time construction progress, the environment, overall well-being of the city, mobility, transport and climate change. In addition, it will serve as a portal to citizens for e-governance operations.[71][72] A similar project was started from the Government of Victoria in Australia. The project will include real-time data visualization of public transport and building occupancy, tools for planning analysis, traffic flow prediction, electricity and water consumption forecast. In addition, disaster management and emergency response plans. [73] A DT can change the way we look our cities and living spaces. It can help authorities in resource allocation, urban planning and sustainable development. It can also provide city planners, as well as architects, engineers, builders, property owners and citizens, with the ability to study and analyze city infrastructure in various scenarios and assess future risks, thereby improving the overall performance of the city, its infrastructure but also processes and services. With the participation of all city stakeholders, managing cities through DT can become more democratic as everyone can have an opinion and say what is missing in their communities and how their environment and city services can be improved.

Characteristics of smart cities based on Digital Twins

There are different understandings of the term Digital Twin from different perspectives. Starting from different dimensions, summarizing and analyzing the different current understandings of the Digital Twin and proposing the ideal properties of it, we have its model's dimension, data's dimension, connection's dimension, service's dimension and physical's dimension. Summaring, we have the five-dimensional model of the digital twin as shown in the next Table. The Digital Twins have four major characteristics: Accurate Mapping, Virtual-real Interaction, Software Definition and Intelligent Feedback. Accurate mapping means that the Digital Twin realizes comprehensive digital modeling of urban roads, bridges, manhole covers, lamp covers, buildings and other infrastructures by arranging air, ground, subsurface and river levels sensors in the physical city, so as to fully perceive and dynamically monitor the operational status of the city and finally form the accurate information expression and mapping of the virtual city to the physical city. Virtual-real interaction means that all kinds of traces, such as traces of people, logistics and vehicles, which can be observed in the physical city, can be searched for in the virtual city after they are created. Software definition means that the digital twin of a city creates a corresponding virtual model based on the physical city and uses software platforms to simulate the behavior of city people, events and objects in virtual space. Intelligent feedback describes the intelligent early warning of possible impairments, conflicts and potential dangers in the city through planning and simulation on the digital twin and the function of providing sensible and realizable countermeasures. On the basis of the digital city, the integration of IoT, cloud computing, big data, AI and other new generation IT technologies can guide and streamline the planning and management of physical cities, improving the delivery of citizen services and helping more in the construction of smart city. [74]

rt of Understanding	Ideal Characteristics	Digital Twin Cities	Dimensions
1a.Digital twins are 3D models 1b.Digital twins are copies of physical entities 1c.Digital twins are virtual prototypes	Multi-dimensional/multi-space time/multiscale Dynamic/evolutive/interactive High fidelity/ Highly reliable/high-precision	Accurate Mapping	Model
2a.Digital twins are data/big data 2b.Digital twins are PLM (Product Lifecycle Management) 2c.Digital twins are digital thread 2d.Digital twins are digital shadow	Total factor/all-service/ complete flow scheme/full life circle Virtual-real fusion/ multi-source fusion/heterogeneous integration Real-time update/real-time interact/real-time respond		Data
3a.Digital twins are Physical union platform 3b.Digital twins are industrial Internet platforms	Bi-directional connection/interaction/driving Cross-agreement/interface/platform	Virtual-real Interaction	Connection
4a. Digital twins are simulation 4b. Digital twins are virtual verification 4c. Digital twins are visualization	Model driven + Data driven Simulation verification/visualization/control/ predict/optimize	Software Definition	Services/ Functions
5a. Digital twins are pure digital representation or virtual bodies 5b. Digital twins are irrelevant to entities	models vary from object to object/data vary by feature/services and functions vary according to needs	Intelligent Feedback	Physical

Table 5 Different understandings of "digital twin" in Cities

Identification of the Digital Twin Cities Potentials

In this thesis the analysis of using the digital twin in cities will shown through paradigms five themes: data management, visualization, situational awareness, planning & prediction and integration & collaboration (Table). Through these topics, the potentials of using the digital twin in cities can be understood in order to further maximize the benefits of the digital twin of cities.

Themes	**Applications**
Data Management	- Data processing - Interoperability - Software fusion - Open-source software
Visualization	- Navigation - 3D real-time experience - Multi-spatial and temporal scales - Unified platform - Behavior modeling - Network dynamics - Personalized information systems
Situational Awareness	- Monitoring - Tracking - Localization - Face recognition - Analysis
Planning and Prediction	- Policy evaluation - Simulation - “What if” scenarios
Integration and Collaboration	- Multiple domains integration - Stakeholders’ participation - Citizens’ engagement - Open platforms

Table 6 Themes regarding the potentials of the digital twin in cities

Data Management

Data management is the first and central topic of the Digital Urban Twin. Due to the different dimensions and the huge amounts of heterogeneous data that can be generated and collected by the city, the ability to manage and process data is significant. To solve heterogeneous data, the use of the ontological approach can be proposed to improve semantic interoperability and secure future data extensions. Developing a layered system architecture for the urban digital models is also an option to manage and integrate different data types in the digital twin model. The city's digital twin has already achieved some potential and progress in terms of data management, but some challenges still prevent it from fully realizing its benefits. For example, the processing and integration of heterogeneous data from different city domains, data standardization, and data sharing frameworks to improve data exchange between software applications are major challenges.

Visualization

The main task in city modeling is to improve the visualizations of the city. Improved visualization can lead to a better understanding of the urban environment and a reduction in design errors. The ability of the digital twin to leverage and integrate with other modeling and visualization applications enhances the visual experience of the digital twin. For example, a visual navigation through the city with different perspectives and scales was developed using VR and augmented reality (AR) technologies, while a full-size VR visualization of the city was demonstrated in conjunction with environmental and other city analysis data.

For instance, improved spatial navigation for digital urban twins was presented using a VR application. Street spaces, infrastructure, high-rise buildings and BIM models can be experienced digitally by navigating through an internet portal, while an urban simulation platform can display a 3D model updated in real time that reflects the queries and analyzes of different domains of the. In addition, various developments have been made to improve the visualization of the digital twin model of the city, for example the incorporation of various urban elements such as vegetation, which visualize both existing and planned environments. In this way DTs Visualaze the city at multidimensional and multispatial scales.

Situational Awareness

The city's digital twin is on its way to connect with the real city to improve understanding and analysis of the city's events and processes. To this end, the digital twin in cities is considered as a fundamental technology for promoting situational awareness for city management and providing a city information model. The city's digital twin can collect, monitor and manage city data. For example, it can reflect the health status of citizens. Display and analyze energy consumption data. Also used to detect movement for public safety activities. Can be used to monitor noise pollution in the city using dynamic models. Providing real-time tracking of information during disasters and monitoring of individuals' behavior with localization of disruptions and potential risks for emergency and disaster management. It is also expected to improve risk analysis and prevention and identify information flows for disaster management. The digital twin of the city makes viable contributions to the perception of different states of the city on multi-spatial and temporal scales and in several areas such as health care, energy management, disaster management, emergency response, mobility and urban planning.

Planning and Prediction

Objects and processes of the past, present and future in the city can be well captured by the city's digital twin model and further analyzed to better understand how the city works. However, the main advantage of digital twins is that they provide useful insights into future plans. Predicting the future behavior of the physical twins to optimize their performance has been highlighted in other fields such as aerospace and manufacturing. Similarly, for the digital twin of the city, the development of possible plans and future city operation scenarios to optimize how the city functions can be a significant benefit. Some research has been conducted to support decision-making processes and encourage alternative policy scenarios. Other applications have been tried to support decision making by providing what-if scenarios for multiple areas of the city. The simulation of possible failures of physical objects in the city using participatory sensors was instructive for improved risk management. Urban development plans as well as urban climate scenarios and simulations can support urban planning decision-making. Planning and forecasting applications linked to the digital twin are useful. For example, the analysis of flood scenarios, the assessment of solar energy potential, the impact of wind flows on the built environment through simulations of weather changes and the urban mobility simulations also.

Integration and Collaboration

The complexity of the city, the interdependencies between its elements such as people, infrastructure, technologies and the interconnectedness of its domains pose the challenge of integrating the information of all these spheres on one platform and providing a collaborative environment for co-design and co-development of the digital twin in a city. The integration of the digital twin can be viewed through two dimensions. The first is the 3D model itself and the second dimension is providing an environment for collaboration between the city's different stakeholders. The use of online and open platforms enables data sharing and promotes stakeholder involvement in urban planning, policy making and evaluation. It highlights that digital twins can engage citizens in creating new plans for the city and improve public decision-making. In addition, the digital twin of the city can be publicly accessible, navigable and discussable by assigning different authorization levels for urban planning.[75][76][77]

Governance

Governments around the world are beginning to address the problems induced by urbanization, such as urban poverty, high urban costs, traffic congestion, housing shortages, lack of urban investment, weak urban economy, rising inequality between people, criminality and environmental degradation. The digital twin, as an inevitable trend of digital transformation, helps cities realize real-time remote monitoring and enables more effective decision-making. New York has developed a strategy to become the world's most digital city with four core areas: access, open government, engagement and industry.[78] The UK Government proposed a Smart London Plan, which aimed to harness the creative power of new technology to serve London and improve the lives of Londoners.[79] Chinese President Xi attaches particular importance to modernizing the national governance system and governance capacity.[80]

Digital transformation is an essential governance choice. Currently, new technologies such as Digital Twins, Big Data, Artificial Intelligence (AI), Blockchain, the Internet of Things (IoT) and fifth generation wireless systems (5G) are rapidly iterating new formats such as the sharing economy or driverless vehicles, digital currency and intelligent Marketing. New concepts are emerging, such as ecology and health, which are attracting increasing attention. Leaders are actively thinking about how their cities can be updated with new technologies, new formats, and new ideas. The amazing advancement of information and communication technology (ICT) provides the basis for intelligent operations. Data and algorithms are rapidly driving the Smart Economy forward. With citizen sharing and co-creation, governments will be able to make smarter decisions and respond more effectively and quickly.[81] The digital twin is the inevitable goal of the digital transformation of cities. Governments will be able to perceive and predict the unmeasurable indicators in the past physical world and make a more comprehensive assessment. The digital twin can become the most important driver of urban wisdom. Decision makers can achieve city governance in a more orderly way. Citizens can participate in urban governance processes and monitor government decisions. The digital twin refers to the state of mutual symbiosis between digital entities and physical entities. Digital twin technology is a technology that integrates data, models and physical entities.

Digital twins refer to the collection of images of entities in the digital world. Digital Twin technology in cities aims to improve the efficiency and sustainability of logistics, energy use, communications, urban planning, disasters, building construction and transportation. In this section several key technologies are listed. Surveying and Mapping technology, Building Information Modeling (BIM) technology, IoT, 5G, Collaborative Computing, Blockchain and Simulation. The above technologies play different roles in DTs. The surveying and mapping technology is the basis for collecting the static data of buildings in cities. BIM technology is the basis for city asset and infrastructure management. IoT and 5G are the foundations to collect dynamic data and feedback effectively. Blockchain technology is the basis for the trust mechanism of transactions, logistics and human behavior. Collaborative computing with 5G is the basis for efficient real-time reactions. Simulation technology is the basis for political support, planning and early warning mechanisms.[82]

Digital twins have things in common with other digital twin systems: self-awareness, self-decision, self-organization, self-execution, and self-adaptation. As shown in the figure below, they are made up of infrastructure construction, urban brain platforms and new applications.

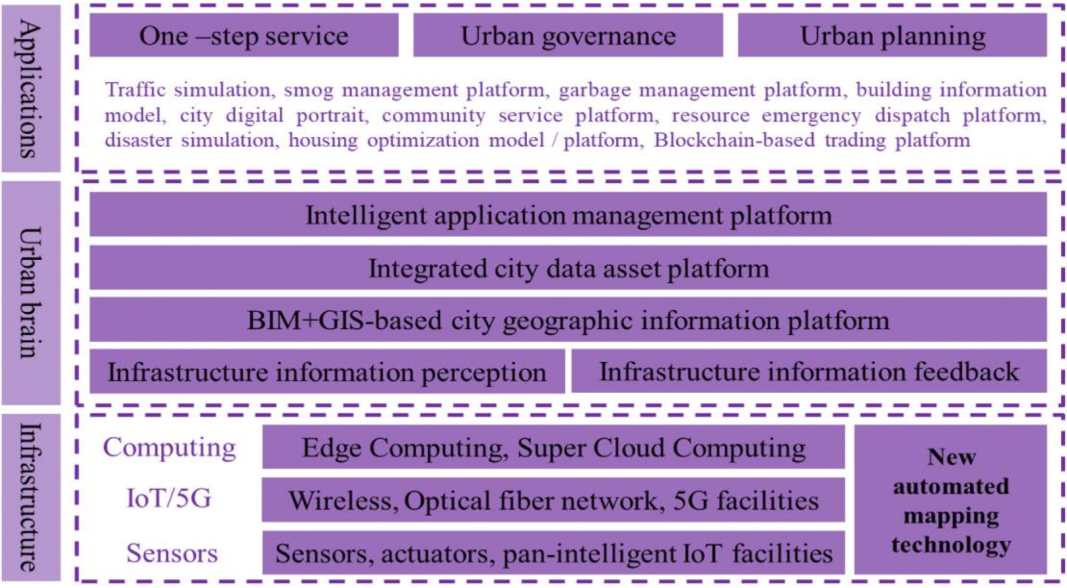


Figure 5 The composition of Digital Twin in cities
Source: Tianhu Deng et al (2021) A systematic review of a digital twin in city

The City Brain platform is the intelligent hub for city operations, which includes: the BIM and GIS-based platform for city geographic information, an integrated platform for city data assets, an intelligent platform for application management, a perception and infrastructure information feedback platform. The urban geographic information platform integrates the city information from the physical world and maps it onto the digital platform, creating the basis for digital twins of cities. The integrated city data asset platform brings together city government data and basic city data collected by sensors, and is an important foundation for smart urban governance. The infrastructure information perception and feedback platform are key areas to connect the digital cities with the physical ones. The infrastructure based on 5G promotes collaborative innovation and data synchronization in both the digital and physical worlds. The intelligent application management platform enables the data by laverazing the emerging AI, Big Data and IoT technologies via AI, operational optimization algorithms and simulation capabilities. Infrastructure construction is the touchpoint and handler for building cities. It provides data support for the urban brain platform, analyzing and executing data and providing real-time feedback to the physical world. The resulting application layer is a modular collection of applications. It invokes City Information Modeling (CIM) and city data to provide scenario services, data services and simulation services. The scenario services include the provision of real-time data on urban architecture, geospatial and environment. The data services include tracing and tracking past behavior of physical entities, monitoring current behavior, and predicting future behavior. The simulation service includes the simulation of time, events and scenarios and simulates services and supports decision making through the design of preliminary plans. In summary, the digital twins will reshape the structures and rules of city administration and will add continuous momentum to the development and transformation of cities. Many of the major cities around the world have launched plans to build their digital twins.[83][84]

Epilogue of the Chapter

DT technology offers an opportunity to integrate the physical world and the virtual world, which can be leveraged to address the challenges faced by diverse sectors. There have been objective advances since the introduction of DT technology, but practical applications and implementations of the technology remain uncharted territory. Sectors such as manufacturing that are pioneers in DTs make the most use of the technology by offering improved products by collecting, analyzing and interpreting data from the DT and retrofitting them into products in the market place. The applications of DTs for any product can be realized over its life cycle, from design to disposal. The benefits of DTs such as remote monitoring and maintenance were particularly realized after the outbreak of the COVID-19 pandemic in 2020. Companies like General Electric have saved billions by using DTs' real-time monitoring capabilities, resulting in reduced operations and maintenance costs. The table below summarizes the applications and benefits of DTs in each sector. It succinctly shows the similarities and contrasting application of DTs in different sectors, along with the benefits it brings.

In broader terms, the applications in different sectors can be summarized as (Figure):

- Optimization
- Decision making
- Remote access
- Training and documentation
- Designing/planning
- Real-time monitoring
- Maintenance
- Safety

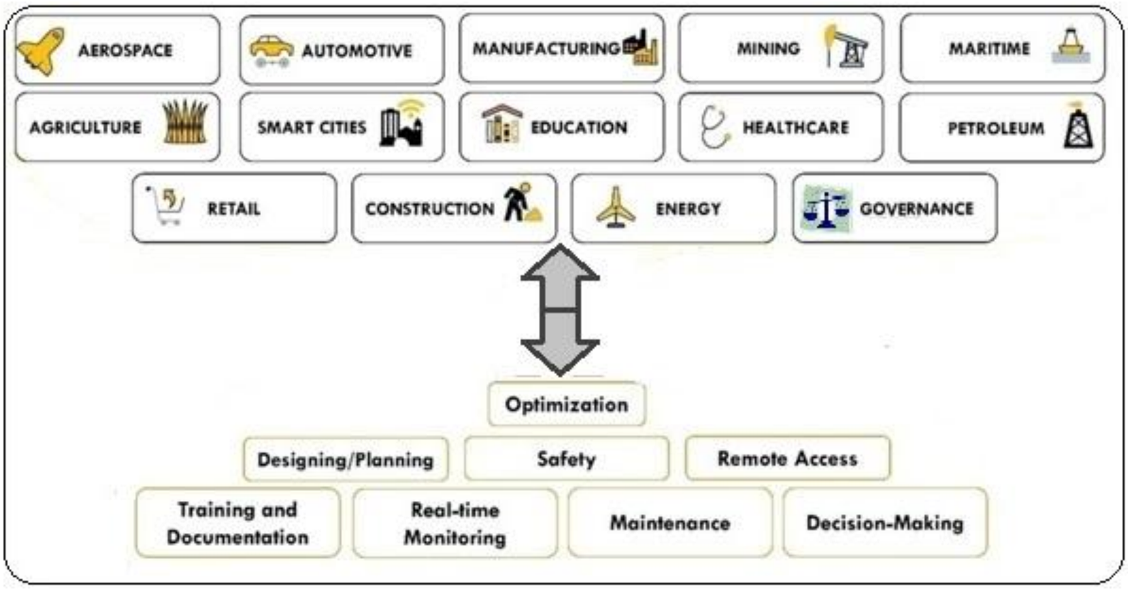


Figure 6 Applications of DTs in different sectors

The multiple uses of DTs make them a helpful tool no matter what sector they are used in. This chapter identified 14 sectors with that of Governance using the technology and reported real cases of DT applications. Although the technology has so many advantages, it also brings many challenges such as any new technology. Its cost and time to implement, lack of standards and regulations but the security and privacy concerns also. Though actual implementation of the DT has yet to materialize, speculation about its potential spurs sways with freedom in the imaginations of researchers. Therefore, it is important to identify and understand the potential of DTs in each sector and implement them for the right application, as it offers numerous benefits, from simulation and prediction capabilities to record keeping and troubleshooting.

Sector	DT Application	Advantages
Aerospace & Aeronautics	✓ Optimizing performance and reliability of the spacecraft/aircraft ✓ Predicting and resolving maintenance issues ✓ Continuous mirroring of the actual flight to predict future scenarios ✓ Designing and testing of product ✓ Simulating and optimizing product and production systems	✓ Safer missions ✓ Maximizes the mission success. ✓ Cheaper spacecrafts ✓ Lower operational and maintenance costs
Manufacturing	✓ Designing and testing of product ✓ Material selection ✓ Customizing the products ✓ Optimizing production planning, execution and control ✓ Predicting maintenance issues and developing a maintenance strategy ✓ Real-time monitoring of production and service ✓ Remote troubleshooting of equipment ✓ Analyzing and forecasting energy consumption ✓ Analyzing user behavior ✓ Recovering the waste ✓ Collaboration tool ✓ Traceability of quality management and process optimization ✓ Energy efficiency management and optimization ✓ Equipment management, remote monitoring, predictive maintenance, virtual inspection, AR maintenance	✓ Better-designed products ✓ Fewer design iterations ✓ Faster and cheaper production ✓ Increases reliability of equipment and production lines ✓ Reduces downtime ✓ Improves decision support ✓ Lower maintenance costs ✓ Less wastage
Healthcare	✓ Optimizing the care, cost and performance of hospitals, operations, staff ✓ Informed and strategic decision making ✓ Personalized cure and care ✓ Detecting and diagnosing disease ✓ Function test ✓ Prediction of equipments malfunction ✓ Optimization of medical resource management ✓ Verification of policy change ✓ Verification of medical and surgical plan	✓ Efficient patient care ✓ Improves success of the treatments ✓ Shorter waiting times ✓ Faster patient recovery ✓ Better equipment utilization ✓ Lower staffing costs
Energy	✓ Finding the best position/location for maximum energy generation ✓ Providing predictive maintenance ✓ Optimizing the strategies for energy network's maintenance ✓ Designing and testing ✓ Training new operators and engineering students ✓ Optimizing distribution of electricity	✓ Increases energy production ✓ Improves assets' safety and reliability ✓ Prevents blackouts ✓ Resource-saving ✓ Improves decision making

Automotive	✓ Predictive and remote maintenance ✓ Optimizing production ✓ Providing personalized/customized vehicles and services ✓ Proving immersive and interactive customer experience ✓ Developing strategies for car races ✓ Training professional racers ✓ Car running status detection ✓ Diagnosis malfunction, maintenance ✓ Simulation of driving process in different environments	✓ Boost vehicle sales ✓ Increased reliability and safety ✓ Improves performance of racing car and racer
Oil and Gas	✓ Tool for understanding and reducing risks ✓ Creating and managing executable work schedules ✓ Identifying any changes in the process and responding accordingly ✓ Optimizing the production and asset performance ✓ Predictive maintenance ✓ Optimize the inspection planning and safety cases around it ✓ Prediction of malfunction ✓ Planning of maintenance ✓ Verification of equipment design ✓ Remote monitoring of equipment status ✓ Data visualization and integration	✓ Lower capital and operation expenditure ✓ Reduces time in optimizing and testing ✓ Boosts production ✓ Improves safety ✓ Reduces emissions ✓ Prevents downtime
Mining	✓ Process/operation optimization ✓ Predictive maintenance of assets ✓ Predicting and optimizing transport network ✓ Simulating and analyzing different scenarios across value chain ✓ Trains new miners, especially for emergency situations	✓ Improves asset and transportation reliability ✓ Cuts down unplanned downtime ✓ Improves processes' efficiency and product quality ✓ Risk-free and stress-free environment
Maritime	✓ Predictive maintenance of vessel ✓ Remote monitoring and diagnostics ✓ Maintenance planning ✓ Optimize the time for the vessel to sail and number cargos to carry ✓ Tool for digitalization of ports, quay walls, buoys	✓ Improves availability, efficiency of assets and missions ✓ Increases reliability of assets ✓ Improves maintenance ✓ Reduces operational costs
Agriculture	✓ Remote monitoring of livestock ✓ Identifying pests or diseases ✓ Managing and optimizing production plants ✓ Monitoring the stocks in warehouses ✓ Evaluating cost-effectiveness of crop management treatments ✓ Planning for vertical farms	✓ Promotes sustainable development ✓ Increases production and thus food security ✓ Better decision making
Education	✓ Tool for communication for visualizing working of systems and sub-systems ✓ Teaching physical twin behavior in the real world under different operational conditions. ✓ Issue identification and problem-solving by immediate feedback on system behavior ✓ Inquiry-based learning during system development and testing ✓ Sharing unlimited resources amongst students ✓ Tool for distant learning students	✓ Better understanding of systems ✓ Simplifies and accelerates knowledge exchange ✓ Ensures safety of students and equipment ✓ Opportunity to explore the complexities and behavior of the physical systems
Construction	✓ Helps in BIM (Building Information Modeling) ✓ Problem-solving against real-life scenarios. ✓ Tool for future projects. ✓ Decision-making regarding feasibility of project, material selection, energy analysis and management, procurement, supplier selection, sustainability issues, etc. ✓ Monitoring and assessing condition and integrity of building continuously	✓ Reduces overall design process and associated cost ✓ Promotes modular construction activities ✓ Avoids costly design mistakes ✓ Promotes incorporating sustainability ✓ Easier to keep track of all the changes and its effect

	✓ Optimizing maintenance and services in the building ✓ Monitors logistics processes ✓ Conserving heritage assets virtually that need demolition ✓ Resource efficiency enhancement and knowledge exchange	
Retail	✓ Providing tailored customer experience and suggestions ✓ Optimizing logistics and supply chain ✓ Inventory and aggregate planning ✓ Demand forecasting ✓ Real-time monitoring to implement new non-linear supply chain fulfilment models ✓ Store layout planning ✓ Decision making in the cases of emergency or disruptions such as COVID-19	✓ Better products and services ✓ Improves sales ✓ Sustainable inventory reductions ✓ Decreased operational cost
Smart City	✓ Resource planning and management ✓ Testbed for new ideas ✓ Help in the decision-making process ✓ Real-time monitoring of construction progress, mobility and traffic, environment and overall wellness of the city ✓ Planning emergency response for disaster management ✓ Studying and analyzing city’s infrastructure and assessing any future risks ✓ Platform to facilitate comments and suggestions by every stakeholder	✓ Improves the accessibility of specific areas ✓ Promotes stakeholder’s participation in decision making and support their involvement and consultation ✓ Improves city services ✓ Fosters sustainable development
Governance	✓ Enhancing efficiency of service provision ✓ Enhancing accountability and transparency ✓ Encouraging equity in resources allocation and monetization ✓ Opening new ways of interaction between different urban stakeholders ✓ Enhancing democracy, cooperation and equality	✓ Potential large scale implementation ✓ Enhacing privacy and social control ✓ Interfere with democratic spaces ✓ Transparency as privacy for data collection on citizens ✓ Providing accountability and liability with transparency in terms of use of data and purposes

Table 7 Applications and advantages of DTs in different sectors/industries

3. Framework of Digital Urban Twins

More than half of the world's population lives in urban areas. As a result of the rapidly increasing rate of urbanization, cities are facing enormous challenges in meeting the housing, infrastructure, transport and energy needs of their urban population and urgently need new ideas and methods to solve these problems. The purpose of urban change and sustainable development must be to enable people and nature to thrive together across generations. Urban systems must come together to achieve this outcome, as cities are fueled by complex systems of interconnected resources and networks. The key challenges of our generation are also systemic: reaching net-zero, climate resilience and the circular economy are system-level challenges that require systems-based solutions. Therefore, our cities need systems-based policies, strategies and tools that enable us to understand and manage urban change to achieve its purpose. Fourth Industrial Revolution technology – represented by the digital twin approach, together with reforms of policies and mechanisms that help us to better understand systems and intervene more effectively. Used by cities to redesign and optimize their urban planning and operations, their governance and service models, and their planning methods. This allows them to upgrade iteratively. Managing the city as a system of systems with a focus on better outcomes for people, society and nature requires the integration of all industries serving the built and natural environment. It also requires the connection of the physical, digital and human worlds.

The Digital Urban Twins map the physical city in digital space by constructing a virtual version of the city. Its goal is to solve the complexities and uncertainties of urban planning, design, construction, management and services through simulation, monitoring, diagnostics, prediction and control. Establish concurrent operation and interaction between the physical and digital dimensions of the city. The digital twin in the city pursues three visions: 1) more intensive and efficient urban production and operations, 2) livable and comfortable urban living spaces, and 3) a sustainable urban ecological environment.[85]

Regarding urban production, digital twin technology is used to intelligently analyze complex scenarios related to flows of people, goods, energy and information. Examples include optimizing urban space layout, relieving traffic congestion at complex intersections, simulating and practicing natural disaster responses, and scientifically formulating emergency evacuation plans. The aim is to gain insight into urban operational patterns, reduce administrative costs and improve citizens' quality of life. In urban life, digital twin technology is used to monitor the performance of urban components, predict failures, avoid risks and ensure the safety of residents. Using digital twin technologies, hospital, classroom and community services can be created through virtual-real interaction and customization. In terms of emission reduction, digital twin cities can help city managers and experts to: 1) evaluate and optimize ecological characteristics, 2) make a comprehensive diagnosis of different policies to implement CO^2 emissions and select optimal solutions, and 3) the efficient operation and to promote the maintenance of energy facilities and tracking of the carbon orbit. These actions can help cities achieve carbon neutrality.[86]

The development of a digital urban twin requires nine elements that represent a 4+5 framework. The 4 refers to the four core elements, namely: 1) infrastructure 2) data resources 3) platform capacity and 4) use cases. These elements provide the internal energy and the digital basis for the digital twin. The 5 in the framework encompasses the five most important external supporting elements of the digital twin. These are: 1) strategy and mechanisms 2) stakeholders 3) funding and business models 4) standards and evaluation and 5) cybersecurity.[87]

Currently, the construction of digital twins in cities still faces many challenges. The increasing use of data increases the risk for digital security and privacy protection, there is a lack of interdisciplinary human resources and industry knowledge, and innovative business models have yet to be developed. According to research, 66.7% of digital twin projects in cities are currently funded by government investment. Therefore, social capital and business investment still need to be improved.

Technical solutions are clearly necessary, but they are not enough. Technology must be developed in a human-centric manner. The ultimate goal is to promote social justice and inclusion to protect the rights of individuals and the positive business power that transforms cities, empowering both the weak and the strong, making the city more livable and harmony between people, city and nature.[88]

For a urban-level connected digital twin programme to be successful, it must also address human and organizational factors. It must address: ethics, skills and commercial, legal and regulatory solutions.

A program for connected digital twins must be socio-technical. This ensures that every organization benefits from improved decision-making and that connected digital twins achieve better outcomes across the economy. A socio-technical change program for connected digital twins is the way to better outcomes for people, society and nature. Looking to the future, the effective development of the digital urban twin needs to be encouraged by governments, businesses and other relevant stakeholders. Governments should: 1) fully coordinate top-level top-down design with bottom-up basic demand and stimulate the motivation of citizens and organizations to innovate 2) design more cross-industry digital twin scenarios around individual demand and supply with 3) build an urban-twin data system with hierarchical classification to ensure distributed security and privacy, and 4) build a multidisciplinary and comprehensive talent team for collaborative innovation.[89] In conclusion and with more simple words, Digital Urban Twins are digital representations of the physical built environment in our cities, including urban transport networks, buildings and infrastructure connected to the data in and around them. A digital urban twin is rendered in virtual reality (etc. virtual 3D replicas). Using powerful supercomputers, electronic sensors and cutting-edge data analysis and visualization technologies, Digital Urban Twin integrates both visible and invisible features of the built environment in an interactive format. Wearing 3D glasses or a VR headset, one enters a realistic replica of a place and can explore it on many scales, down to the level of a pedestrian looking at individual streets and buildings. Its main purpose is to bring all available data together into a common, easy-to-understand 3D visual model to help people make better decisions about their projects. Digital Urban Twins allow users to aggregate complex data from many sources at scale and simulate future outcomes (CO^2 emissions, temperatures, energy consumption, pedestrian flows, traffic, financial revenues). As the world prepares to tackle climate change, we need tools like this more than ever to better understand, plan, predict and implement our sustainability, social and economic goals while responding in real-time to a changing world around us react around.[90]

Urban DT Use & Benefits

Digital Urban Twins streamline the planning, operations, financing and decision-making to reduce emissions in large, complex projects. Benefits from significant cost savings, productivity gains and reduction of CO^2 emissions, etc. We can find usage in:

- Cities
- Districts
- Campuses
- Airports
- Manufacturing plants
- Urban Infrastructure
- Utilities
- Oil & Gas

Digital Urban Twins are both engineering tools and business tools that provide users with an unprecedented level of collaboration, analysis, visualization and prediction.

Digital Urban Twins - Planning the Cities of Tomorrow

A city consists of two dimensions: the physical dimension, which includes its geography and infrastructure and the social dimension, which includes its citizens and culture. However, as we moved into the second quarter of the 21st century, there was a worldwide recognition of a third dimension: the digital dimension. So many of the activities that make up the fabric of a city - urban planning, financial transactions, social sharing, real-time public transit updates, and more — now take place in the digital world. So it should come as no surprise that there is now a global movement to harmonize and democratize these virtual events by creating interoperable digital platforms where decision makers and other stakeholders can monitor, simulate, predict and monitor the current and future state of their city can plan. Known as Digital Urban Twins, these platforms provide a crucial interface and organizational tool for smart city technologies. Digital Urban Twins are already changing the way cities are planned, built and managed. Examples of this can be found in cities in every continent.[91]

Digital Twins at Urban Scales

Digital Urban Twins comprise static 3D models of a city's physical objects along with dynamic predictive models of their behavior, driven by real-time inputs from city-wide sensors. Such sensors and models represent changes in the physical dimension of the city in the digital dimension. For example, water levels of their rivers, wind speeds, how full their trash cans are or real-time positions of transits - as well as the social dimension of the city, such as how full a train is, what type of business is in a building or what major cultural events are taking place. Well-designed Digital Urban Twins are more than just a tool for city managers. They encompass many different systems that together form a diverse, interoperable, accessible, inclusive and secure data ecosystem where many different actors can gain insights that improve decisions.[92]

Digital Twins In The Smart City Domain

An overview of domains that use Digital Twins in smart city projects is presented in this section. In the Figure below there is a high-level architecture for a city-scale Digital Twin, including the key technologies, main components, main data sources and application domains.

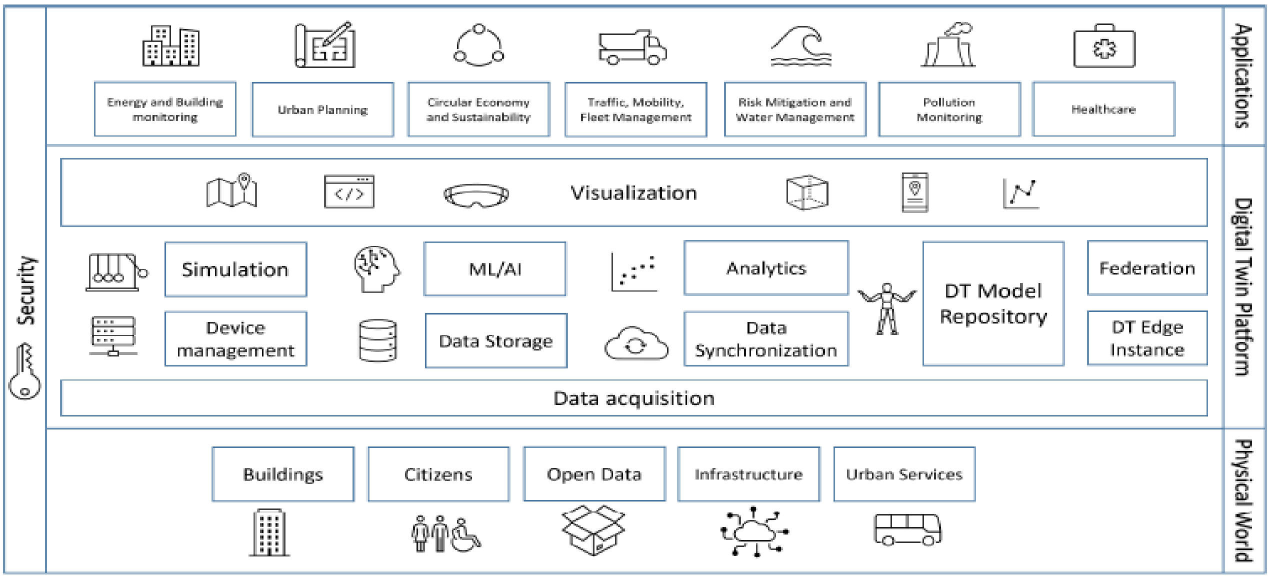


Figure 7 A high-level overview of a City-Scale Digital Twin
Source: Mylonas et. al. (2021) "Digital Twins From Smart Manufacturing to Smart Cities: A Survey", IEEE Access

Its main components are the real-world data sources and significantmajor application domains tackled thushat have been covered so far. Data acquisicollection mechanisms forward data from the real- world to the main components of a Digital Twin platform, where e.g. ML/AI-based approaches can be utilizsed to process such data and then performrun simulations based on the models available in the Digital Twin model repository. Through the available visualization components available (e.g. web portals, VR, 3D models and maps) and depending on the specific application domain, results can be delivered to end- users or other systems while security traverses the wholflows through the entire stack.[92]

Energy Management

Energy is one of the most important resources for running a city, from large metropolitan areas to small towns or communities, everything from buildings, transport, infrastructure and services require enormous amounts of energy. No wonder the energy sector was perhaps the first smart city application area to be included in digital twin technology. Interest in building and grid energy efficiency and the availability of smart energy meters have certainly led to new digital twin approaches in the energy sector. The large amount of real-time building energy performance data available through the proliferation of IoT technologies provides the necessary basis for energy efficiency calculations. Building Information Modeling (BIM) technologies are used as a means of visualizing the energy performance of buildings, providing energy managers and officials with more user-friendly platforms on which to base their decision-making, while improving citizen participation and raising awareness of energy-related issues. The use of artificial intelligence and machine learning technologies is being used extensively to process large amounts of data and extract useful results that can help prioritize energy-related retrofits and interventions. Another strength of digital twin models, which excels when it comes to energy efficiency but also when it comes to monitoring the structural health of infrastructure, is the ability to accurately simulate different scenarios and provide city officials and planners with solid knowledge of the achievable outcomes or hazards related with the operation of the city.

Urban Planning

The increasing number of inhabitants in metropolitan areas, the limited space and the limited resources for urban expansion make the urban planning and simulation of proposed measures and buildings essential for the sustainability of the implementation. Digital twin applications can help in this regard while increasing citizen participation in policy making. Urban planning processes pose challenging tasks for the city administration in terms of optimal decision-making, selecting policy packages that have the least negative impact on other aspects, and citizen involvement and acceptance. The digital twin model offers integration possibilities for a variety of technologies that generate the required amount of data to support this complex decision-making process. City environments are displayed dynamically using point cloud technologies. This enables a real visual presentation of city structures that are supposed to change long before anything is actually implemented. The scenario simulation is also of paramount importance to provide both officials and citizens with feedback on positive and negative outcomes of the planned interventions.

Circular Economy & Sustainability

At present, there are many activities related to Circular Economy and Sustainability and IoT. We see a small body of work introducing digital twins into this area of application, particularly in cases where remanufacturing and sustainable production are the goal, or in the sustainability assessment of buildings. However, the applications of digital twins for circular economy and sustainability in a smart city currently seem to be quite limited. There is a belief that this will change in the years to come, and scenarios such as waste management appear to be amenable to the potential use of digital twins.

Traffic, Mobility & Fleet Management

There are opinions that some of the first DUTs were implemented as part of efforts to develop mapping services (Google Maps, HERE WeGo, etc.), since the creation of detailed city maps essentially involves extracting features from the real world and converting them into digitals. In essence, the digital twins can provide a basis for the development of services from either a private company perspective or a city authority perspective. From the perspective of the private sector, the currently dominant business model is to build a closed-sourced digital twin of the physical world in order to use it to provide mobility-oriented functions. The rise of autonomous driving has pushed this direction further, either through the availability of such features in available passenger vehicles or through efforts by companies like Tesla but and Uber and Waymo which aiming to produce fleets of self-driving taxis. A digital twin of the urban space can help provide more advanced autonomous driving functions, better passenger mobility and timetable planning, etc. Essentially, in the case of simulating autonomous driving features in simulation environments that match those in the real world, Digital Twins are a direct response to this real-world business use case in the automotive industry.

Digital twin technologies appear well-timed to utilize the advances in autonomous vehicles and appear to align well with the current ongoing wave of mobility electrification. There is an obvious interest from both private and public entities to use such approaches to advance the autonomous driving vision and implement better traffic management, and at the moment this seems to be a strong application scenario for using Digital Twins. Since the field is still fairly new, some of the challenges we see in most Digital Twins areas are still pretty evident here: standardization, scaling, security and privacy concerns are all issues that seem to be outstanding. However, it also seems likely that advances in smart cities, vehicle electrification and digital transformation of the car industry will help speed things up in these aspects.

City Resilience

The past years, effects like climate change in the form of an increasing number of extreme weather events appeared in our lives. A large part of such events are related to water, in the form of either draughts or floods, while the current projections for sea level rise in the coming decades are cause of great concern and alarm. The word ‘resilience’ has entered the public debate surrounding cities and communities, indicating an awareness of the magnitude of the impact such events can have and the importance of risk mitigation mechanisms. To a large extent, these events have fueled a renewed interest in using the technologies developed in recent years to develop smart city solutions for crisis management. Using all the available information to provide a more accurate picture of the real-world parameters affecting the outcome of such events. Although it is obvious that risk mitigation could potentially be an important application area for Digital Urban Twins but at the moment it seems that the number of implemented DT-based prototypes and solutions is quite limited. One might also note that the scope of implementation in almost all such deployments is quite small, which might indicate hidden costs and complexities in implementing and operating such Digital Twins in practice.

Monitoring of Pollution

Pollution monitoring is vital in any city as reducing pollution is a key factor in the health and well-being of citizens. We are starting to see Digital Twins applications deployed in this area, with a clear focus primarily on air quality and secondarily on noise pollution in urban environments.

The collection of air pollution data from sensors coupled with the model’s ability to apply computational fluid dynamics algorithms provides the ability to actually visualize air pollution levels through the city. The propagation of noise through city structures can also be simulated using a 3D GIS layer. Providing advanced public Digital Twin based visualization options of these common urban issues could also aid in raising citizen awareness on environmental issues and adopt a greener approach to the use of polluting resources and operations.

Healthcare in Smart Cities Using DTs

The use of sensors and IoT within healthcare has grown rapidly in recent years. The health-related sensors and related services in smartwatches and smartphones are now a commodity. Google and Apple have made publicly available statistics as regards changes in mobility patterns of people using these companies. This duality of targeting health-related applications at both a personal and a community level is gradually being transferred to the Digital Twins as well. Sensors from both personal devices, like smartwatches, and smart city sensing infrastructure can be employed to enable such applications. In this context Digital Twins of human organs can help to simulate the effect of treatments, while smart cities can use Digital Twins to respond to potential and actual dangerous situations as regards health, e.g., air pollution affecting the health of citizen inside a certain urban area. In terms of the challenges involved, the most frequently cited challenges are privacy and ethics, and policy-related, as health data is inherently very sensitive, followed by challenges related to implementation.

Research Projects

There are a daily growing number of research projects on urban-scale digital twins. Until now there have been two main types of Digital Urban Twins prototypes. The first focuses more on 3D representations of the built environment and is aimed almost exclusively at urban planning, while the second and newer takes a more general approach in terms of the data used and applications developed, with additional aspects such as the integration of co-creation and collaborative activities. Below is presented a summary table of research projects implement in big cities around the world.

Table 8 Examples of city scale DT research projects

DT Project/City	Applications	Co-creation	IoT Data	Public UT	Status/Comment
NASA	Asset & Risk Management	None / Limited	Unclear	N/A	Mature, many years in operation
New South Wales DT	Environmental/pollution/traffic monitoring, risk and water management, urban planning	Limited, City authorities	Traffic, Air, Flood	3D map, Web	Mature, in operation, publicly available, several application areas, large-scale
Virtual Singapore	Urban planning, Environmental monitoring, Traffic	Limited, City authorities	Environmental, Mobility via other projects	3D map	Mature, several application areas, large-scale
Herrenberg	Urban planning, Environmental and Pollution monitoring	Yes, citizens & stakeholders	Noise, Air,	3D map, Web, VR	Pilot deployment / advanced research Prototype, focus on VR interfaces
DUET	Urban planning	Yes, citizens & Stakeholders	Traffic, Air, Noise	3D map, Web	Pilot deployment / Research Prototype
SPHERE	Energy in buildings	None /Limited	Energy, indoor N/A environment, Weather	N/A	Small-scale pilot deployment / Research Prototype
LEAD	Last-mile logistics	Yes, multiple stakeholders	Mobility	N/A	Pilot deployment /Research Prototype
Dublin	Urban planning	City authorities, Universities	None/Limited	3D map	Demo Prototype
Zurich	Urban planning, environmental and pollution monitoring	City authorities	Traffic, Environmental, Energy	3D map, Web, AR	Under active development. Multiple applications built
Rotterdam	Port Management, Energy, Emergencies response	Limited, city/port authorities	Port traffic and environment, traffic, energy	3D map	Under development /Proto type
Antwerp	Air & Noise Pollution, Traffic monitoring, Urban planning	Limited/ City authorities	Air, Noise, Traffic	3D map, Web	Prototype
Helsinki	Tourism, Urban planning	Yes, other smart city projects	None/Limited	3D map, Web, VR	Prototype
Boston	Urban Planning	Limited	None/ Limited	3D map	Under development
Shanghai	Urban Planning	None/Limited	None/Limited	3D map	City-scale prototype
Amaravati	Urban Planning	Led by local government	Unclear status	N/A	Unclear status
Wellington	Urban Planning, Traffic monitoring	Limited	Land & Air traffic, Parking	3D map, Web	Prototype

Examples of Cities and its implementations

The example of Herrenberg in Germany

The city of Herrenberg in Germany is the prototype of an Urban Digital Twin. Herrenberg's executives used the Digital Twin to consult with citizens on projects like a local mall. The goal in creating the complex virtual model was to help city planners to understand better the urban environment. The German city has been recreated in VR, with the use of technology developed by the High-Performance Computing Center Stuttgart (HLRS). The Digital Twin is a hyper-realistic computer model of the city that simulates the entire urban environment. The city was created using a process called spatial syntax, which uses a 2D outline of the city as a framework for spatial analysis. Large datasets on air quality, traffic flow, pedestrian traffic prevalence and other dimensions of urban life were collected and mapped onto the framework. This allowed the virtual model to predict things like the likely paths car or pedestrian traffic might take from one point to another. The team also integrated data from geographic information systems and traffic management systems to develop additional layers of complexity, even creating realistic models of how wind and emissions move through the city. They also developed an app that residents could use to indicate how they felt in different places in the city. The team used the data to create an immersive 3D virtual reality model that brought the city to life. [108]

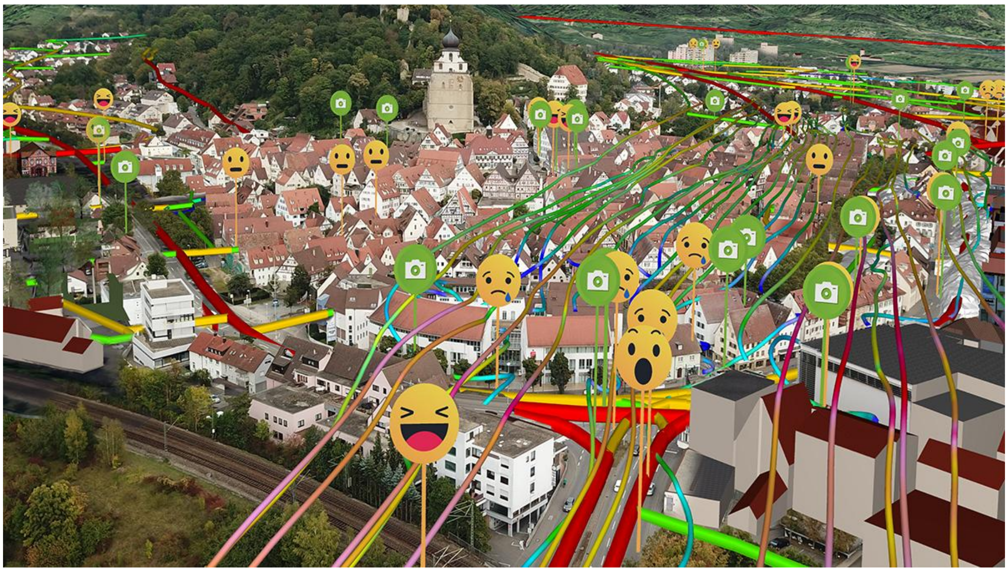


Figure 8 Feedback integration from citizens concerning locations around the city
Source: www.hlrs.de

The City of Helsinki

The city of Helsinki has won the top prize in the Digital Cities category at the global Year in Infrastructure Awards in 2020. It won the award for its Digital City Synergy project, which helps the city improve collaboration and derive more value from its city models. The main theme of Helsinki's Digital City Synergy project is to specify the roles of different city operators and the benefits of working together in developing a digital city. Digital urban development and the utilization of modern analytic methods enable the city to simulate the end results of decision alternatives in a variety of ways before any decisions are even made. The method based on information models also enables data analysis and system monitoring to improve future planning and anticipate possible issues. Helsinki uses Micro Station, Context Capture and Open Cities Map to generate and update a reality mesh and information model of the 500-square mile city area for its digital twin, which includes CityGML. It established a connected data environment using Project Wise with Open Cities Planner as the visualization and collaboration platform for all stakeholders, including the public. The open, digital solution enables better decision-making by connecting the right information to the right stakeholder and provides a reliable digitalized data infrastructure to support sustainable smart city initiatives. The Kalasatama Digital Twins report is an example of the benefits gained from the Digital City Synergy project. Helsinki has been piloting the Digital Twin model especially in the Kalasatama district, preparing high-quality 3D city models in great detail and offering them to all operators and partners in the form of open data. The City of Helsinki hopes that its city model platforms promote diverse product development, research, education and innovation in the field and contribute to increasing awareness and understanding of the vast potential of digitalization in urban development.[98] [99]

Figure 9 Helsinki's data connected environment
Source: smartcitiesworld.net

The case of 'Virtual Singapore'

Virtual Singapore is a dynamic three-dimensional (3D) city model and collaborative data platform, including 3D maps of Singapore. The creation of the 'Virtual Singapore' platform is supported by the National Research Foundation (NRF), Prime Minister's Office, the Singapore Land Authority (SLA) and the Government Technology Agency of Singapore (GovTech). The cost of the program estimated about 73$ million for the development of the platform as well as research into latest technologies and advanced tools. In the official website that presents the creation of this platform, can be read that it is based on the intention to enhance the following four categories of activities:

Virtual Experimentation

Virtual Singapore can be used to examine the coverage areas of 3G/4G networks, provide realistic visualization of poor coverage areas and highlight areas that can be improved on in the 3D city model.

Virtual Test-Bedding

Virtual Singapore can be used as a test-bedding platform to validate the provision of services. For example, the 3D model of the new Sport hub with semantic information within the Virtual Singapore could be used to model and simulate crowd dispersion to establish evacuation procedures during an emergency.

Planning & Decision-Making

Virtual Singapore is a holistic and integrated platform to develop analytical applications (i.e. Apps). For instance, an app could be developed to analyze transport flows and pedestrian movement patterns. Such applications would be useful in non-contiguous urban networks such as our parks and park connectors in Punggol.

Research & Development of the project

When Virtual Singapore's rich data environment is made available to the research community with the necessary access rights, it can enable researchers to innovate and develop new technologies or skills. The 3D city model with semantic information offers researchers many opportunities to develop advanced 3D tools. Virtual Singapore has enabled public authorities, the private sector and even the community to leverage the information and systems capabilities for policy and business analysis, decision making, idea test-bedding and community collaboration.

In addition, on ‘Virtual Singapore’s’ case, special attention was paid to the visualization of the benefits and potentials of solar energy production **(**Figure**)** and to data concerning demographics, climate and traffic. The ‘Virtual Singapore’ was developed by the French software corporation Dassault Systèmes. The name of the urban scale Digital Twin for Singapore is 3DEXPERIENCity. For its creation, real-time data and data collected from various public agencies were used. One of the main goals of ‘Virtual Singapore’ is to achieve more sustainable solutions in terms of urban planning and more efficient energy consumption. The specific potential of the 3DEXPERIENCity solution lies in the fact that it enables a detailed simulation of extremely large environments. However, one of the key issues of this project is the difficulty of acquiring the resources this urban scale Digital Twin would require in order to be kept up to date.

Figure 10 Virtual Singapore's Solar Panel Production
Source: www.nrf.gov.sg

Singapore plans digital twin bike lanes to promote healthy, low-carbon travel for citizens

Singapore is actively promoting cycling as part of its low-carbon strategy and to engage citizens in physical exercise. The authority uses digital twin technology to confirm road conditions through a 3D model, taking into account factors such as road obstacles, tree shading, surrounding facilities, traffic connections and other information, in order to plan bicycle lanes and bicycle parking lots in the digital space. At the same time, relevant departments can assess the safety level of bicycle lanes using the digital twin model to ensure citizens' safety. Government departments have repeatedly promoted the construction of bicycle lanes and related facilities to improve the convenience and safety of cyclists, encourage healthy travel and promote energy saving and carbon reduction in the city.[94]

Digital twin of the Docklands area in Dublin

The open (publicly available) Digital Twin of the Docklands area in Dublin is a digital representation of a virtual replica. In this project Digital twins were giving the opportunity to citizens to update its data by their self. At a first stage, citizens give feedback to the model being deployed online and at a second stage their feedback is sent to the relevant group, such as the researchers who developed the urban mobility model or the city council, who provide the urban IoT data. This allowed for easier dissemination and transparency to the public before putting any decisions into any practice. This open and public model allows for an additional virtual feedback loop where citizens can interact and report feedback on planned changes in the city. Citizens can also interact with components to tag and report problems in the area. The Digital Twin also allows for additional experimentation where 3D data is necessary, such as flood evacuation planning, for urban planning of skylines and green space allowing users to interact and report feedback on planned changes.[94]

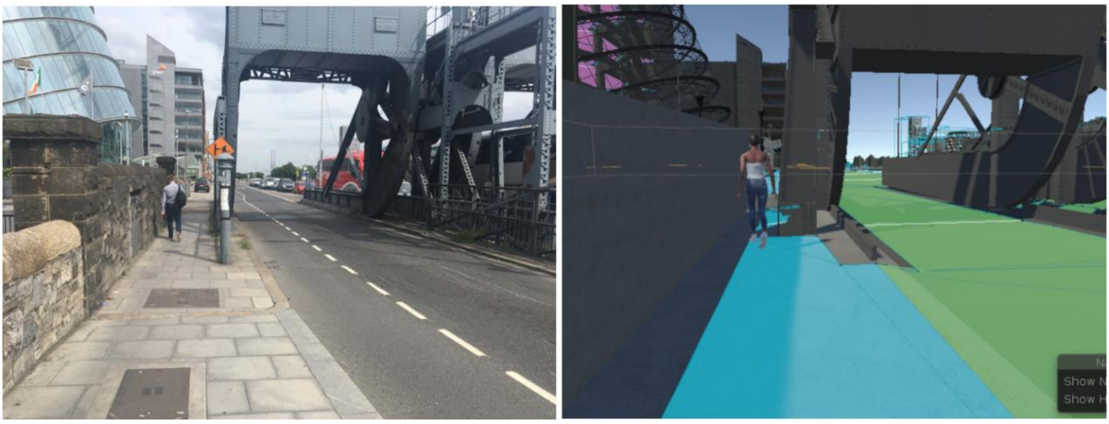


Figure 11 Physical and Virtual Comparison in Dublin's DT
Source: smartdocklands.ie

The case of the Urban Digital Twin of Zurich

Another case of urban scale Digital Twin that is worth mentioning is that of the city of Zurich. This project is known under the label 'Virtual Zurich'. Among the data that have been visualized for this project are data concerning noise, air pollution, mobile phone radiation, solar potential and visualization of construction projects (Figure).

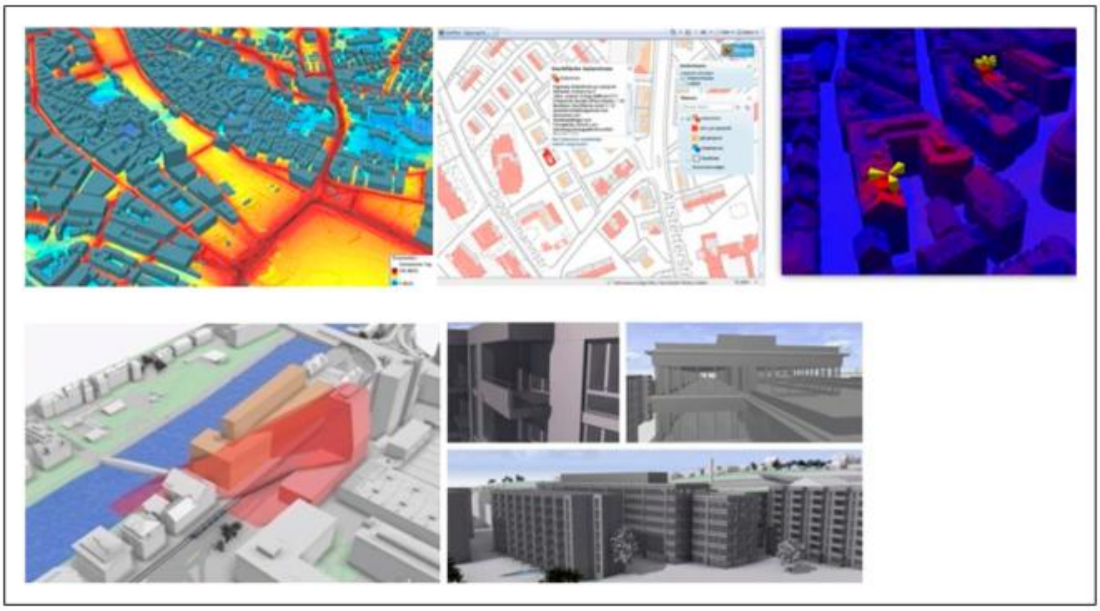


Figure 12 Established applications on Zurich's Project
Noise (upper left), Air pollution (upper centre), Mobile phone radiation (upper right), Solar potential (lower left) and Visualization of construction projects (lower right).
Source: City of Zurich.

As an important part of the smart city strategy of the city, the Digital Twin of the city of Zurich was developed for supporting decision-making in the city via a digital spatial image. In their work, Schrotter and Hurzeler presented how the city's digital twin may can improve city administration and support urban planning decision-making. They described the process starting from data collection based on the spatial data of the existing 3D city model. The Zurich's Digital Twin enables the visualization of street spaces, underground utilities and chosen public buildings with higher levels of detail. For improving interoperability and data retrieval, spatial data and metadata were defined and described in detail in a federal act that was the base for developing the Digital Twin governance framework. To enable the use of the Digital Twin, open governmental data is being utilized in order to facilitate contributions from the different stakeholders and their accessibility to the city data. Furthermore, a geoportal was developed that facilitates the collection of the automatically updated geodata and a viewer was developed for the Digital Twin, which enables the visualization of the 3D components of the city and ongoing construction projects.

In addition, several benefits and various applications were exercised and found useful in the context of urban planning decision-making, such as comparing and evaluating different urban development scenarios, integrating urban climate issues in development plans and facilitating public participation in planning. The Digital Twin of the city of Zurich shows high potential for improving the visualization and planning of the city and the inclusion of stakeholders. However, the model requires further development. For instance, there is a need to increase the level of detail of the buildings and other city elements, integrate BIM (Building Information Modeling) and GIS **(**Geographic Information System**)** applications to maximize the use of their potentials and reduce the time between data updates and the 3D model processing time. [101]

Camebridge

The design of the urban-scale DT for Cabridge (Figure) integrates the development processes of the technological platform with the different political-administrative institutions, the private entities and some citizen representatives. In this sense, the project tries to connect the goals of the DT with urban politics and collective demands. This cross-sectoral approach to multi-level governance is a good example of integrating public and private interests in efficient urban planning.

Local public institutions organized workshops, conducted preliminary context studies and organized interviews with various public and private stakeholders. At the participating meetings, stakeholders identified some critical issues: road traffic and pollution, limited capacity of energy infrastructure, need to update housing policies and create new jobs. Starting from these addresses, there are presented several two-dimensional what-if cartographies developed with GIS techniques, representing possible scenarios useful to guide the construction of the DT project and new urban strategies. The authorities themselves, from the materials they consulted and produced, reconstructed the needs of the public administration and the demands of the citizens, which will represent some of the technical requirements of the future and which can be summarized as follows:

a) Communicating data that influence choices (transparency of data-driven decisions)

b) Enabling citizens to use the DT (accessibility to data and the possibility of remote feedback to establish a rapid dialogue between the Public Administration and citizens).

The method proposed for the development of this DT reinforces the role of knowledge co-production and the arduous but necessary dialogue between territorial actors to connect the technological network with the strategic development goals of the city. This methodologically absolutely interesting approach has slowed down the development of the overall infrastructure of a DT type model, which seems to be still in an embryonic phase.[93]

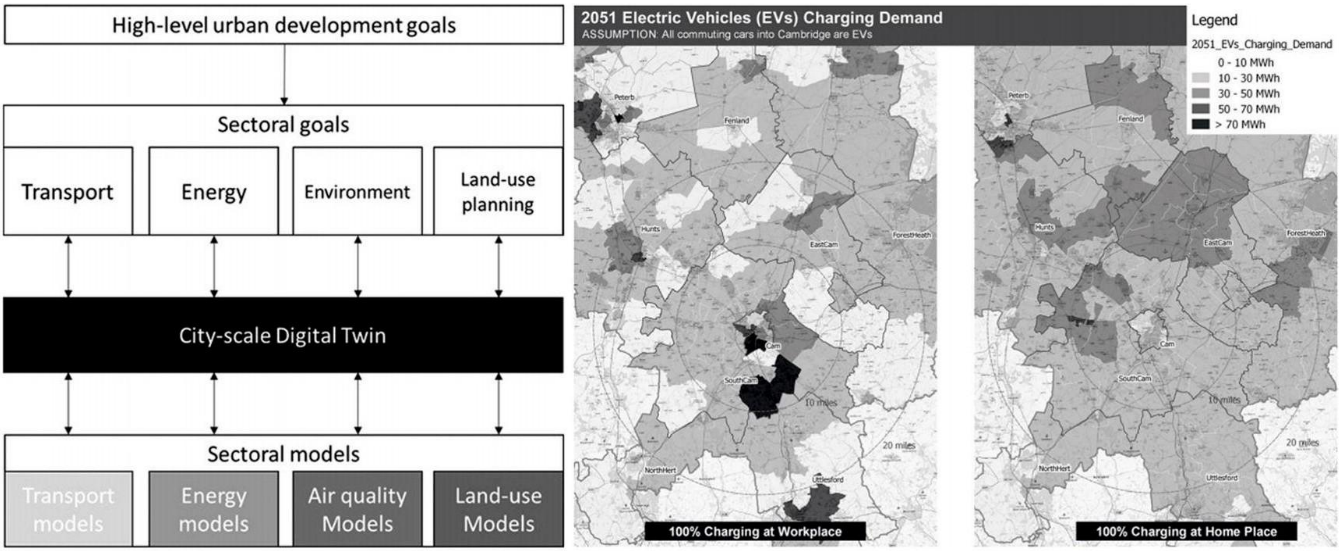


Figure 13 The Digital Twin as a potential coordination tool between planning levels in Camebridge's case
Source Notcha et al., 2021 A Socio-Technical Perspective on Urban Analytics: The Case of City-Scale Digital Twins

In evidence, some 2D forecasting scenarios quantifying local energy needs based on urban densification settlement models and an electric mobility scenario.

Below is an evaluation table summarising the salient features of the first 6 case studies above.

Case Studies				
	Cambridge	**Zurich, Dublin, Helsinki**	**Herrenberg**	**Singapore**
DT types	**Static and managerial**	**Dynamic-evolutive**	**Dynamic-evolutive and collaborative**	**Dynamic-evolutive**
Scale	**Supra-municipal**	**City, sub-areas, district**	**City**	**City-State**
Purposes	Multi-level governance and platform for cooperation between different planning levels	Orientated towards data-driven preventive assessment, creation of simulative and predictive scenarios for support in sustainable urban development policies/actions	Consensus building, involvement of interested citizens, democratisation of decision-making processes	Development of a high-tech decision support platform
Technologies	GIS-processing	GIS-BIM, Laser Scanner, UAV (Unmanned aerial vehicle), IoT, software Open Source	GIS-BIM, IoT, AR/VR, software Open-Source	GIS-BIM, high-resolution satellite imagery, Remote Sensing, Deep Learning, Machine Learning, AI
Experiments	♦ Traditional urban planning surveys prior to the elaboration of the project ♦ Simulation of local energy demand in a 'what if' scenario of electric mobility considering future housing and work policies	♦ Simulations of crisis and prevention scenarios (floods and run-off, thermal stress, exposure to pollutants) aimed at developing site-specific strategies ♦ Urban microclimate analysis (ventilation, shadow study, solar radiation)	♦ Augmented reality applications (AR/VR) in public events and workshops ♦ App development for data collection ♦ Mobility and traffic simulations for awareness-raising on anthropogenic pollution issues	♦ Climate simulations from city-scale (City-GML) to building-scale (BIM) with different application tools integrated in DT ♦ 3D tree census with semi-automated technological procedures ♦ Maximum accuracy of the built environment
Strengths	♦ DT as an instrument of coordination between planning levels ♦ Strategic analysis of the local governance structure ♦ Involvement of citizen representatives	♦ High-tech 3D model ♦ Simulations in critical climate scenarios ♦ DT models in open data	♦ Multi-participatory activities ♦ Advanced technological tools (AR/VR) and GeoApp data collection ♦ Simulations from sensors data	♦ Realistic DT and advanced technological instrumentation ♦ Open-space characterisation (3D vegetation) ♦ Macro-micro energy/climate scenarios from measured and simulated data
Weaknesses	♦ Undeveloped virtual 3D model ♦ Limited simulation capabilities	♦ DTs do not take into account the morphology of open space ♦ General low interoperability and users involvement (workshops, tools, feedback and reports) ♦ Few simulations from IoT-synchronised data	♦ Lack of proactive proposals and/or scenarios ♦ Lack of relationship with government and territorial governance	♦ Risk of lack of data transparency ♦ Lack of a co-design system and participatory processes

Table 9 Summary of contents and comparison of case studies above

The LEAD Project

LEAD project will create Digital Twins of urban logistics networks in six urban nodes to support experimentation and decision making with on-demand logistics operations in a public-private urban setting. City logistics solutions will be represented by a set of value case scenarios that address the requirements of the on-demand economy and the pressures caused by the increase of parcel deliveries while aligning competing interests and creating value for all different stakeholders. Each value case will combine a number of measures (LEAD Strategies):

a) Innovative business models.
b) Agile urban freight storage and last-mile distribution schemes.
c) Low emission, automated, electric or hybrid delivery vehicles and
d) Smart logistics solutions.

Scenarios will incorporate opportunities for shared, connected and low-emission logistics operations by considering four innovation drivers: Sustainability - Zero Emission Logistics, the Sharing Economy, Technology Advancements and the emerging Physical Internet (PI) paradigm.

Cost, environmental and operational efficiencies for value cases will be measured in 6 Living Labs (Madrid, The Hague, Budapest, Lyon, Oslo, Porto). The long-term vision of LEAD is to design a framework for smart city logistics, thus setting the foundations for the development of large-scale city Digital Twins. By exploiting contextual, sensor and real-time operational data, city-scale Digital Twins will facilitate the comprehension of the dynamics of logistics networks in the city and the integrated planning and management of freight movement.[100]

Expected Impacts

Impact 1

Clear understanding of cost-effective strategies, measures and tools to achieve essentially zero emission city logistics in major European urban centers by 2030.

Impact 2

New tested, demonstrated practices and solutions for better cooperation between suppliers, shippers and urban/ regions policy makers (planners)

Impact 3

Clearly provide inputs for the preparation and implementation of Sustainable Urban Logistics Plans (SULPs), Sustainable Urban Mobility Plans (SUMPs) and other planning tools (big data and real-time traffic management)

Figure 14 LEAD Strategies for shared-connected and low-emission logistics operations
Source: www.leadproject.eu

Barcelona

Barcelona is one of the latest cities to start building a digital twin of itself. The data-driven replica of the city, currently in a testing phase, is expected to be operational by 2027, when it will be used as an urban design tool to shape the city's future development.

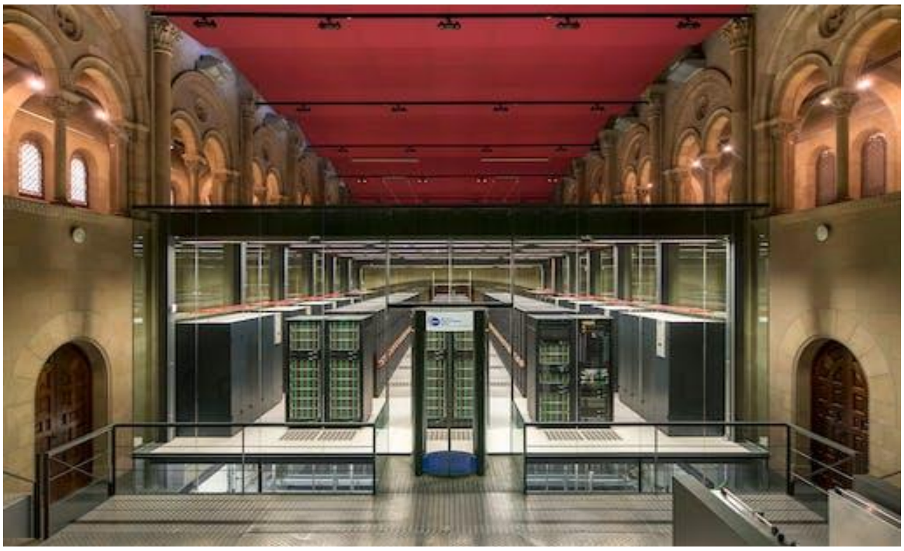


Figure 15 The MareNostrum supercomputer from Barcelona's Supercomputing Center
Source: archinect.imgix.net

The digital twin will be housed in the Mare Nostrum supercomputer, one of the most powerful data processors in the world, located in the chapel of the city of Torre Girona. Originally built in the 19th century, the chapel was rebuilt in the 1940s after the Spanish Civil War and is now on the campus of the Polytechnic University of Catalonia. The chapel has housed the supercomputer since 2005.

For city officials, the digital twin offers urbanists, architects and planners the opportunity to test urban theories and projects before implementation to understand their impact without physically disrupting the city. Rather than implementing bad policies and then having to go back and fix them, we save time by making sure those decisions are right before we execute them. Use of the supercomputer give the opportunity of certainty that the urban planning process isn't just based on clever ideas and good intentions but on data that allow to anticipate its impacts and avoid the negative ones.

A recent relevant application in Barcelona is found in the project of city superblocks. The city had begun developing superblocks as car-free mini-neighborhoods around which traffic flows. Launched in response to the city's fight with air pollution, the plan aime to reduce vehicular traffic by 21%, freeing almost 60% of the streets from cars.

Figure 16 Barcelona to create car-free "superblocks"
Source: Barcelona plans major increase in 'green' zones", BBC News, www.bbc.com, 2020

Despite promising air quality effects within the superblocks themselves, a supercomputer analysis found that the impact on emissions in the wider area was negligible. In summary, air quality is better in the superblocks themselves, but pollution has increased in the adjacent streets where displaced car traffic has shifted. This does not mean at all that the super blocs are bad, on the contrary, they have had a positive impact in other ways, but it shows that they are not a panacea when it comes to air pollution, so they must be combined with other measures to reduce emissions.

Figure 17 Section cut of pedestrian space condition with planted trees in a Barcelona superblock
Source: Barcelona plans major increase in 'green' zones", BBC News, www.bbc.com, 2020

The supercomputer is now being used to realize Barcelona's vision of a 15-minute city that would allow citizens to access all daily services within a 15-minute walk or bike ride of their homes. Analysis performed using the digital twin could include gentrification to increases the economic value of neighborhoods, access to transportation or to call attention to a higher population of older people in need of specific health, social or transportation infrastructure. The project will enable the city to make rapid planning decisions to combat climate change. The goal is to make Barcelona carbon neutral by 2050. [119]

Barchelona's agreement with Bologna to develop Digital Urban Twins

Barcelona and Bologna have signed an agreement involving two of the three most powerful supercomputers in Europe, the Barcelona Supercomputing Center (BSC-CNS) and the CINECA consortium of universities, together with the University of Bologna, to develop a Digital Urban Twins for public policy. The aim is to improve public policy and governance in both cities. The cooperation agreement has a term of three years with the possibility of extending it by a further three years. The intention of Barcelona and Bologna is to become a leader in the field of digital city management and to promote the development of a European digital infrastructure for city politics and to promote a European network of digital twins. This will also help to find external funding opportunities for digital twins through European programs. [120]

Specifically, the two cities share the goal of moving towards evidence-based decision-making in public policy and impact assessment, particularly in the areas of urban mobility, energy, urban planning and measures to reduce greenhouse gas emissions. The project examines how digital twins contribute to the target of the mission for neutrality in carbon and development of the smart cities. Both cities have committed to working together to maximize the energy consumption of the necessary infrastructure and to use renewable energy. The creation of this common working platform offers the possibility to exchange important scientific and technological advances between the BSC and the CINECA and to work together on the standardization of data to ensure European interoperability.

The Slovenian National Digital Twin

The International Research Center on Artificial Intelligence (IRCAI) in Slovenia is currently developing a national-level DT, incorporating a novel AI model that constructs the digital flow of a nation vis-a-vis situational awareness, in order to augment decision making processes on the enterprise and government levels. The digital twin consists of five central AI-powered elements: nowcasting, root cause analysis, causal modelling, prediction, anomaly detection. Collectively, these elements provide a real-time, digital replica of the societal flow, which enables policy and decision makers to experience a never-before-seen level of intelligence obtainment optimization. The digital twin model of situational awareness is robust and hence provides a number of critical use cases. Perhaps the most relevant applications of the digital twin in our present state of the world include health, supply chains and the Coronavirus Pandemic in which Slovenia succeeded to prevent an exponential growth of infections. This shows the power of needing a constant stream of data to mitigate dilemmas before they fallout.

The imperative for real-time analysis of data flow is a pressing concern in the healthcare industry. A digital twin model is imperative in order for physicians and top medical authorities to implement the correct before-the-fact procedures and treatments. Without a digital twin model, the scale and scope of healthcare measures will never be comprehensive enough to solve root-cause issues. Branching off from healthcare, if implemented, the integral digital twin model facets of anomaly detection and causal modelling would have had incredible success in mitigating the global Coronavirus Pandemic and the model's now casting feature would have prevented the devastating rupture of worldwide supply chains. Indeed, the Coronavirus Pandemic serves as a premier wake-up call for modern society as an AI-fueled situational awareness which must be deployed by nations everywhere, not just Slovenia.

In addition IRCAI builds a digital twin for Monitoring and Predictive Systems on a global scale and constructs a true system in which all of the world's operations are observed through an interconnected, AI-driven lens. Moreover, this dynamic viewpoint of worldwide processes enables real-time observation and analysis, multilingual intelligence absorption, a means to connect-the-dots between various nation-based procedural nodes, and the ultimate ability to predict outfalls of certain sequences of events. Hence, greatly augmenting the decision and policy making process of governing bodies everywhere.

Slovenia's novel approach towards situational awareness is to extend it to the realm of mapping social dynamics, a type of model that artificial intelligence is only beginning to scratch the surface of. The reason why it is difficult to control and predict social dynamics is a result of its massive variability and volatility, as well as a lack of available data and the absence of a comprehensive global system. Therefore, the only way for AI to be useful in this highly variable environment is to automate the situational awareness model of the digital twin in order to enable real-time analysis and deploy this system across networks everywhere. An example of an automated situational awareness system that Slovenia has developed includes the IRCAI's Events Registry System which IRCAI is using to understand the social dynamics of various global challenges.[121]

New Mexico, USA

New Mexico is located in the southwest of the United States, covering an area of about 314,900 square kilometers. It is the fifth largest state in the United States, with a population of about 2,097,000. In 2019, the state passed the Energy Transition Act (ETA), which proposes that the state shall become a clean energy leader and achieve 100% clean energy by 2050. Founded in 2009, Cityzenith, a US software company, proposes to transform cities through digital twin technology to make them cleaner and healthier, and contribute to the “Clean Cities – Clean Future” vision. As a result, the State of New Mexico has partnered with Cityzenith to develop SmartWorldPro, a digital twin city platform, to help build new “smart infrastructure” and achieve carbon neutrality goals.

Cityzenith’s digital twin city platform, SmartWorldPro, is a tool for building planning, management and operations. The platform is used by architects, contractors and asset managers to carry out site selection, planning, design, construction, operation, maintenance and sales.

To overcome the difficulty of integrating data from different sources such as BIM, GIS and IoT, SmartWorldPro has significantly expanded and upgraded its data import and integration capabilities, providing the ability to import hundreds of data types into a common dashboard. Using 3D templates, users can quickly scale from a single building to a portfolio of hundreds or even thousands of buildings, including information on rooms, floors, textures and major equipment. At the same time, users can customize rendered scenes to their liking, with visualization tools such as colour palettes, preset objects and base maps.

SmartWorldPro has built Mapalyze, an application store for building professionals, as a library of analysis tools. Mapalyze provides users with AI-based analysis such as solar analysis, viewpoint analysis, sociological analysis, traffic studies and climate impact simulations. In addition, SmartWorldPro offers a variety of deployment methods, including customized solutions, software as a service (SaaS) and software development kits (SDKs).

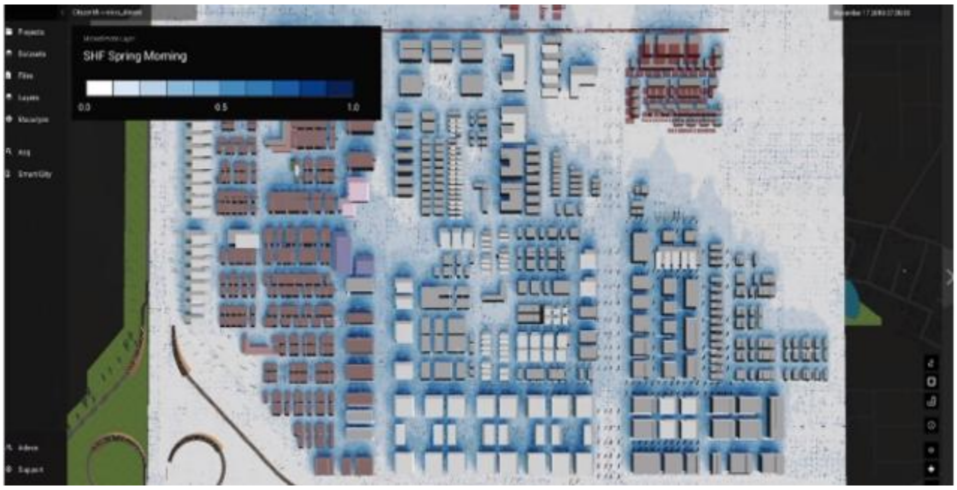


Figure 18 Analysis of the effect of temperature in different seasons in New Mexico’s Case study
https://cityzenith.com/

Cityzenith is already reducing carbon emissions, maximizing savings and improving efficiency with its digital twin platform in cities such as New York City, Pittsburgh and Phoenix. In Albuquerque, New Mexico’s largest city, Cityzenith conducts modelling and works to create smart, connected communities for cities, large venues and even entire states. As a digital twin platform for city infrastructure, in the future, it could reduce city operating costs by 35%, increase productivity by 20% and reduce carbon emissions by 50–100%.[94]

New South Wales in Australia

Developing a digital twin proof-of-concept model to support multistakeholder participation in urban planning

The New South Wales (NSW) Government, in partnership with the Data61 department of the Commonwealth Scientific and Industrial Research Organisation (CSIRO), has developed the digital twin proof-of-concept model: a complete, real-time, accurate and reliable 4D framework model that projects a physical environment that can enable realtime spatial-based data sharing and collaboration to help policy planners and project developers better design and manage the future of cities.

The digital twin platform is the largest 3D modelling project in Australia’s history. It uses sensor-equipped fixed-wing platforms to capture images of large areas with high accuracy, with the end result expected to cover 3,392 square kilometres and include a 3D grid map of Sydney‘s western region captured at less than 6cm pixel resolution. The platform extensively aggregates data from multiple sources, visualizes historical data from government, industry, communities and models buildings and natural resources above and below ground using data obtained from water, energy and telecom utilities.

The digital twin platform integrates digital engineering assets, building information models and real-time application programming interfaces (APIs) for managing assets, public transport, air quality and energy production. For example, using the digital twin platform and blockchain technology, NSW puts information on building design approval, data verification and construction management on the blockchain, which provides the basis for subsequent smart asset management. In addition, NSW has developed a minimum viable product and upgraded it from a two-dimensional space to a four-dimensional visualization platform that allows developers to use digital twin technology to create digital models of cities and communities.

The digital twin platform is integrated with the NSW Spatial Collaboration Portal to provide real-time information and a data service centre allowing people to search, find and share spatial information. Through the integration of the platform and the portal, digital services are created based on user needs, enabling user-centric, accessible and convenient government services. It also enhances public engagement capabilities and promotes the NSW Government as a global model for service and digital innovation.[122]

NSW’s spatial digital twin project can now produce an online Western Sydney map of 22 million trees with height and canopy attributes, more than 540,000 buildings, nearly 20,000 kilometres of 3D roads and 7,000 3D strata plans, which can effectively help infrastructure builders to plan soundly and digitally before projects are implemented and to facilitate regional economic activity.

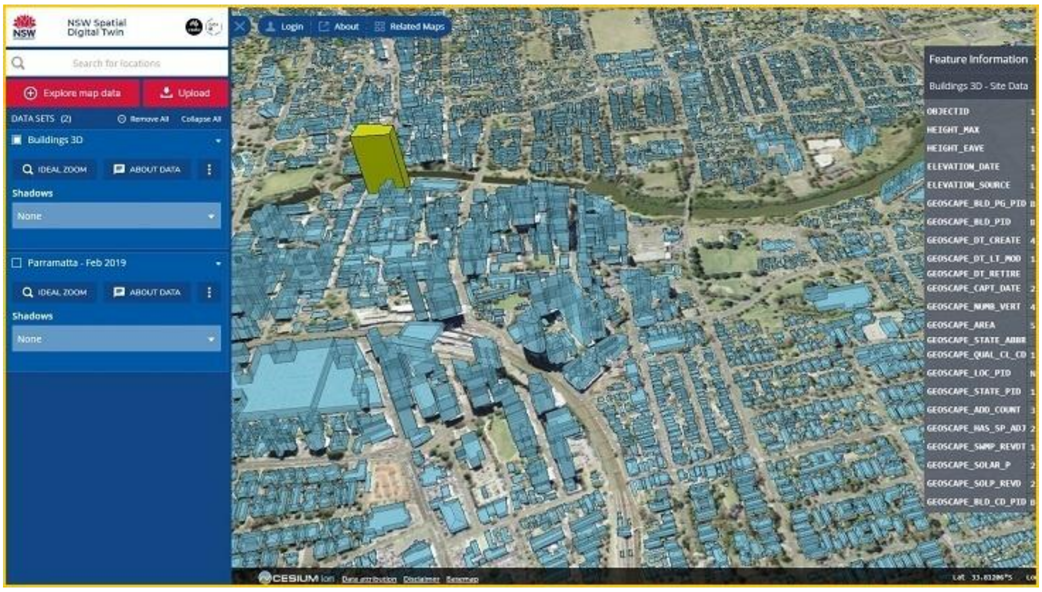


Figure 19 NSW launches Spatial Digital Twin
Source: https://ia.acs.org.au

France

The Grand Est region of France has built a dashboard based on a 3D experience platformof Dassault Systemes. Digital Twin technology helps Grand Est strike a balance between a virus prevention measures and the city's disadvantages. For example, multidimensional data fused to build a dashboard for city management during period of COVID-19 lockdown. In addition, the dashboard can track changes in the number of people hired and those who are unemployed in the region because of a pandemic, thus monitoring the impacts on the regional economy. All of the information above can be displayed in a panoramic or partial view as needed, helping administrators learn details of the pandemic's situation like in case of COVID-19 in a timely manner and effectively formulate policies regarding the location, length of time and specific measures to dealing with it.

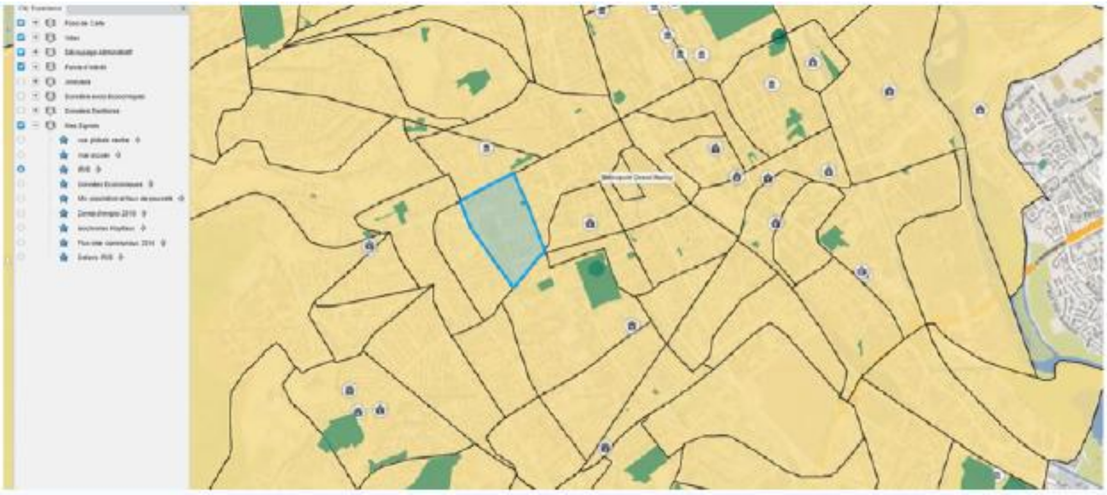


Figure 20 Interface of the Dassault Systèmes dashboard in the Grand Est region of France use case
Source: www.weforum.org

Rennes

Rennes is the second largest city in north-western France and a major tourist destination. Metropolis Rennes and Dassault Systemes are working together finishing a virtual copy of the city to significantly reduce costs in metro planning and construction. The ultimate purpose is the development of a digital model of the city for urban planning, decision-making and management and as a service to citizens. The 3D platform is a collaborative environment that allows stakeholders to collaborate and communicate in the design of innovative projects, products and services. During the planning and construction of the metro passenger railway in the Maurepas district of the city, digital twin technology was used to collect and merge, share and analyse urban-scale data to develop a 3D model of the subway through simulation. The model can display both more macroscopic information, such as the topography of the terrain around the subway station, and more detailed information such as solar panels on the roof, emergency escape routes, and shady paths. At the same time, it is able to simulate the impact of subway construction on traffic signals, foot traffic in bus stations, commute times and changes in community architecture. The city's virtual model can streamline the decision-making process. Through 3D models and simulation technology, Virtual Rennes can present the development of various programs for decision makers in a graphical and extremely easy-to-understand way, helping urban planning departments to transform experience-based decisions into data-based decisions. Based on digital twin technology, it can reduce subway station construction time by 70% and finish three months earlier. In addition, it can help to create multi-governance systems, set up communication channels for stakeholders, enable the participation of urban planners and the public, and also strengthen communication and cooperation between government, citizens and other stakeholders in the early phase of the project. In this way, a public consensus can be built on the effectiveness of the digital twin. [122]

Georgetown, Malaysia

To drive in economic development, Georgetown uses a digital twin platform to assess new project feasibility, infrastructure capacity needs and sustainability, support land-use reallocation, and attract investment. By creating an urban data platform, Georgetown is able to collect and aggregate large and diverse datasets from public and private domains, including planning schemes, environmental statistics, street facility information, energy and water consumption, building and population data. Continual monitoring and visualization of public properties such as roads and bridges through integrated sensor data helps maintain cities, monitor threats (both natural and man-made such as fire, earthquakes, surface temperature rise and floods) and help to predict impacts of multiple types and levels of risk in the city. The digital twin platform can be used to analyse, simulate and visualize the relationship between regional planning scenarios and economic, social and environmental outcomes. These information can then be used to assess the feasibility of new city projects. In addition, the platform enables urban stakeholders to predict and solve problems such as potential hazards, congestion, urban overheating, waste emissions and unemployment. In addition, it can provide interactive services for residents, such as immersive shopping experiences to improve the quality of life in cities. In conclusion, Digital Twin technology is helping Georgetown to: 1) Rethink its land use plans and urban sustainability regulations 2) Anticipate and analyze urban risks to reduce the damage they cause and help the city overcome them quickly in the future 3) Achieve lower infrastructure costs, increase municipal revenues and attract investment 4) Improve quality of life, resilience and environmental sustainability.

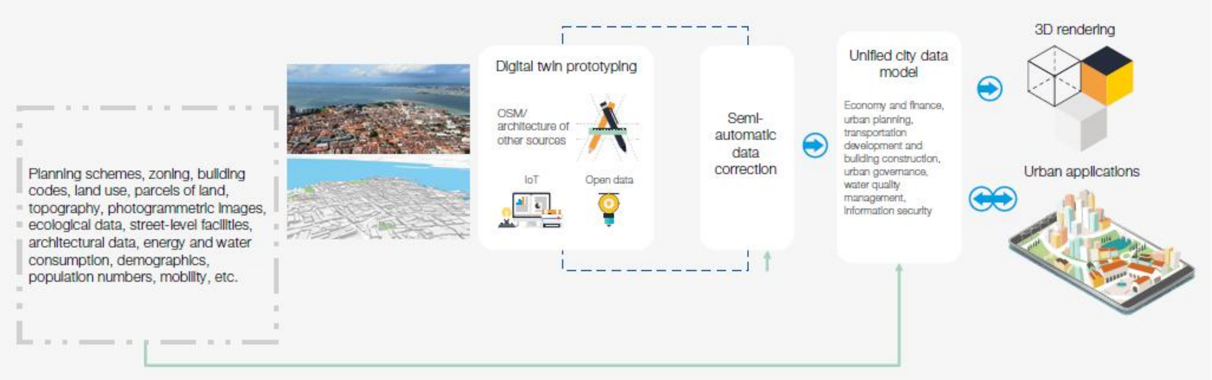


Figure 21 Digital Twin Project of Urbanetic in Georgetown of Malaysia
Source: CAICT

China

Digital twins of Hong Kong (Neuron City)

China is one of the world's leading test areas for smart cities. Hong Kong is building an urban-scale digital twin platform to map space, people and activities of the physical city to a virtual city. The digital twin includes GIS, BIM, IoT, cloud computing and AI. Although many pilot projects exist, they tend to follow a similar profile with targeting at testing or showcasing computational capabilities, rather than at solving real-world problems. They are often too fragmented, isolated systems like transport or security and generally with a low level of artificial intelligence. Therefore, in Hong Kong a platform is builded that is able to overcome these challenges. With the help of city planners and design team, they were able to bring this to life. The platform maps the physical spaces and people to a virtual city (i.e. the digital twin) to monitor, predict and control aspects of the physical city by incorporating a closed-loop data stream. This has lead to solve rather complex problems in the urban lifecycle.[93]

The first-stage work was a city scale information model (CIM) platform operating system. The prototype included the following functionalities:

- 3D modelling and spatial analysis
- Visualisation of simulation data and statistics
- Building data dashboard
- Parametric design module
- Real-time data visualisation and analysis.

The project integrated an IoT data management platform. They produced a demo of the complete design scenario and implemented a machine learning algorithm to provide predictions using urban-scale data.

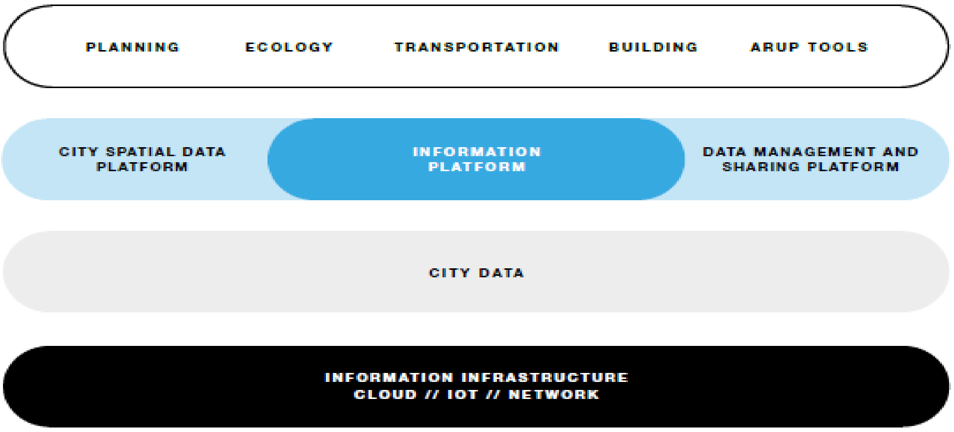


Figure 22 The Neuron City framework
Source: www.arup.com

The value of the first-stage work consisted of building the CIM platform which was used in several projects to demonstrate the added value to the design. The platform adds value by integrating data for collaboration and decision making and by developing innovative city prediction and control applications. The value generated can be captured in the two examples below:

- **Distribution of house prices**

  As part of Neuron City, online house price data was collected and visualized by location. This provides a quantitative basis for decision-making and a better insight into the housing market.

- **Multi-source spatial analysis**

  They used Landsat's multispectral remote sensing image to achieve a specific distribution of land types. This has enabled them to achieve remote sensing with a higher level of accuracy and precision.

Future plans for this platform includes establishing a data pipeline, collaborating across the ecosystem, and developing partnerships with integrators and suppliers to continue to solve complex urban lifecycle problems. In the next few years, there are plan to launch a market-ready commercial product with the goal of adding more intelligence and learning to the platforms.

Shenzhen, China

Mawan Smart Port uses digital twin technologies to achieve smart port operations and navigation management.

Established on September 30, 1986, the Mawan Smart Port in China's Yangtze River Delta is a prime example of how a traditional bulk terminal can be upgraded and transformed into an automated terminal. The port uses digital twin technology to create a 1:1 realistic replication of static port scenes and a data-driven simulation of dynamic port operations, providing features such as real-time dynamic replications of port operations and flexible switching of equipment operations perspectives, visualization of trailer operations paths, search and positioning of equipment and containers, 3D spatial management of yard and container services and statistical analysis of operational efficiency.

By accessing the container data in the container service management system, Mawan Smart Port dynamically generates containers in the 3D version of the digital twin with the same location, appearance, number and type as their physical counterparts, enabling users to store containers quickly and you can directly control them. This feature also helps users to select suitable containers with specific dimensions, thus improving yard and container service management efficiency.

Mawan Smart Port can access historical operational data to create historical operational overview and help to find the causes of operational anomalies and thus offer solutions. As a result, a knowledge base is created that helps with later on-site planning and with the formulation and optimization of operational plans. It is also possible to access real-time operational data, enabling real-time operational monitoring, overcoming the shortcomings of video surveillance and improving the efficiency of real-time operational planning. In addition, it is possible to access operational plan data to review and optimize the plans.

With the help of digital twins, artificial intelligence, 5G applications, the BeiDou navigation satellite system, automation, smart ports, blockchain and other technologies, Mawan Smart Port's load sharing efficiency is 15-20 times higher than that with manual methods and the overall operation efficiency is around 30% increased. Efficient management of operations and movements is achieved with the Smart Port.

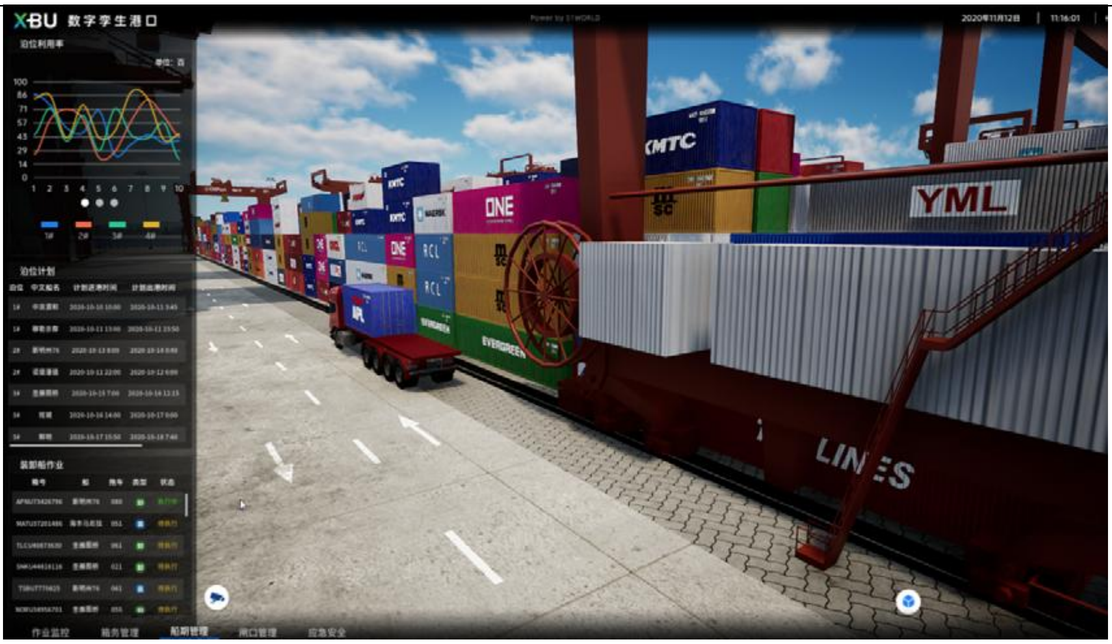


Figure 23 Realistic recreation of a static port scene
Source: www.51aes.com

Kunming, China

Building a traffic database with digital twins to improve overall traffic management

Kunming is the capital of Yunnan Province in China and one of the most important cities in western China. In order to reduce rush-hour traffic congestion and improve the city's traffic health index, Kunming has built a city traffic database based on digital twins so that city traffic managers can monitor and control the city's traffic operations.

Kunming Intelligent Transportation Project uses digital twin technology to achieve 1:1 digital replica of roads, vehicles, traffic facilities and geomorphic environment elements. As a result, data is generated, for example, about the road network, the vehicles on these roads and the condition of the equipment (e.g. traffic lights) which is projected in real time with high accuracy and precision into the three-dimensional digital world.

By combining data from radar, video, internet and road network, the platform achieves an accurate quantitative assessment of urban road operations at macro, meso and micro level. Macroscopically, it provides an overview of the city of Kunming, for example, shows the congestion delay index and regional traffic speed, provides an accurate display of vehicle movement by digitizing vehicles and by fully replicating vehicle trajectories, shows the efficiency of traffic flow at intersections with lane-level indicators such as congestion length , flow rate, speed and delay. It also shows the road safety situation by capturing any road emergencies or traffic violations.

A comparative analysis shows that Kunming's traffic management has been significantly improved by the platform, with average delays throughout the day decreasing by more than 10%. Traffic during the evening rush hours has been largely optimised by an average of 12% (with the highest 20%).

Figure 24 The digital restoration of traffic elements
Source: www.aliyun.com

Xiong'an New Area, China

Digitally monitor the entire city life cycle with the BIM management platform

The Xiong'an New Area is the first area in China proposed the construction of a digital twin. According to the planning outline the city planners want to digitally monitor the whole life cycle of urban planning, construction, management, use, maintenance and repair, and create the BIM management platform for planning and the construction of the Xiong'an New Area. Their target to achieve synchronous planning and construction of the digital city and the physical city.

The Xiong'an New Area BIM platform combines six phases: 1) master planning 2) detailed control planning 3) scheme design 4) construction supervision 5) completion and acceptance and 6) operation monitoring. Its goal is to increase the efficiency of urban management through the use of digital technologies. Under this framework, planners use the “6 BIMs” of Xiong'an New Area: BIM1 (status quo) BIM2 (master planning) BIM3 (detailed control planning) BIM4 (design plan) BIM5 (construction supervision) and BIM6 (completion acceptance).

In the BIM4 (design plan) phase, the platform provides consulting and review services that allow users to perform multilevel and multidimensional comparisons of the spatial arrangement, building height, architectural style and related design parameters of different design plans. At the same time, in combination with the requirements of the relevant design controls, the platform can digitize different types of control elements to enable automatic verification of various design parameters.

Figure 25 Digital twin helps users make multidimensional comparison between different design schemes
Source: www.51vr.com.au

In the BIM5 level (construction supervision), the BIM platform follows an innovative approach to integrate the construction site management into the platform supervision. Before the start of the project, the construction unit must submit a 3D field model of the construction site to the administrative authority in accordance with uniform standard specifications. In addition, the connection of the platform with the intelligent monitoring system for civil engineering in Xiong'an New Area enables interoperability and exchange of data about the construction site e.g. information about people, machines, materials, processes and the environment.

The BIM management platform for the design and construction of the Xiong'an New Area, combined with data collected through sensor devices or the IoT, enables real-time monitoring, early warning and condition assessment of the city. This redesigns urban planning and construction processes and effectively simplifies administration and approval processes.

Urumqi China

A digital twin platform for a land port, optimizing grouping of cargo to reduce transportation costs is builded in Urimqi of China. The digital twin of the Xinjiang International Land Port provides a comprehensive overview of the port's information in the digital space. Through technologies such as IoT sensing and spatial computing, the platform integrates cargo data convergence, automatic matching and optimized grouping, eliminating issues such as over-reliance on labor and low efficiency of manual cargo grouping. Scattered goods from different locations are regrouped and placed on appropriate trains to different destinations, greatly reducing transportation costs and opening a fast lane for goods export. At the same time, the digital twin helps the park to realize intelligent applications such as container positioning, real-time energy consumption monitoring, unmanned driving and automatic vehicle path planning, all of which help promote the intelligent upgrading of the land port park.

Figure 26 Digital twin port platform
https://mp.weixin.qq.com

Shanghai China

Urban digital governance management unit to create a digital twin system for buildings

In February 2021, Shanghai Huangpu District and Huawei jointly selected Nanjing Building as the pilot site for the smallest urban digital governance administrative unit. By integrating cloud computing, big data, AI, 5G and other advanced technologies, the unit creates a digital twin system for the building. The system integrates and accesses data from multiple sources, including:

1) Government data such as home ownership, condition, history and protection needs.

2) IoT collection data such as building vibrations and tilt, smoke sensors, elevators, temperature and humidity and noise.

3) Video AI data, e.g. real-time detection and early warning of various events such as pedestrian flows, presence of smoke, open windows and fire alarms.

4) Other data such as heat conditions, cleaning and disinfection logs, environmental data, subway operations and underground pipe networks. Powered by data, the system delivers digital governance applications such as falling object alerts, people flow controland asset inspection. Shanghai simulated a scene where there is a risk of an object falling from a considerable height.

If someone opens a window in the building and sticks a smartphone out of the window to take photos, the building's digital twin system will immediately detect the danger of falling objects and automatically alert building security guards via their smart bracelets. Once the security forces addressthe situation, the smartphone will be withdrawn and the window will be closed. Then the digital twin system's “vital sign” is restored to “healthy”.

Chongqing China

Digital twin for intelligent construction that helps industry reduce costs and increase efficiency

Chongqing has built an internet platform for smart construction using digital twin technologies. This platform aims to digitize the entire process of project management, construction management and government oversight. For government, the platform enables digital control of the engineering process and provides justification for executive decisions related to project approval and monitoring. For the industry, the platform helps to create uniform standards for engineering and construction data. Builds a modular, software-based and reusable industrial internet platform. Provides high quality application services related to design, production, construction and subcontracting. The Chongqing's Housing and Construction Commission encourages enterprises to use the platform to pilot digital and intelligent construction projects through the use of incentive measures such as pre-sales and performance-based bonus support. At present, more than 100 projects have adopted these platform services, helping to drive the digital upgrade of the construction industry and improve the implementation ability of smart construction.

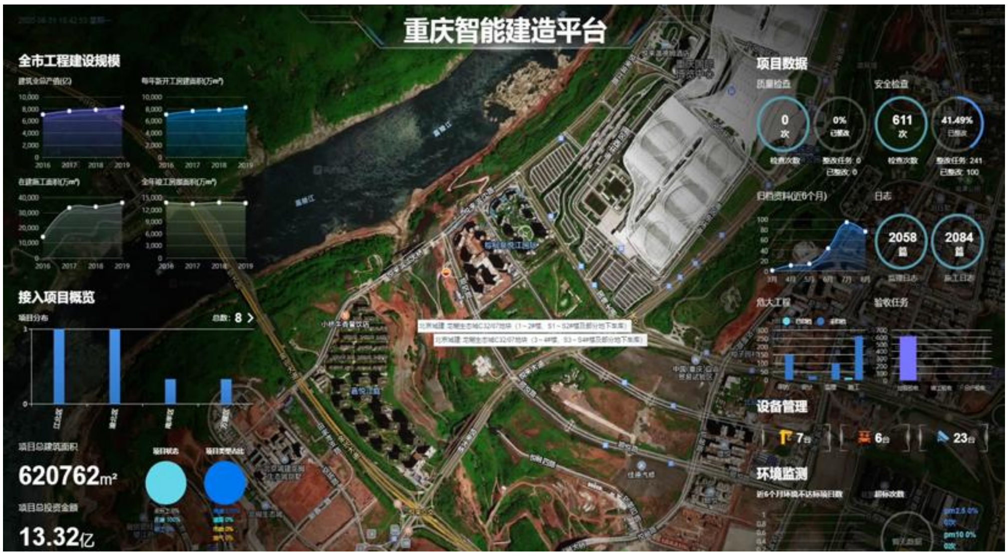


Figure 27 Chongqing's smart construction platform
Source: www.tencent.com

Beijing China

The digital twin of China's International Services Trade Fair to support trade evolution

With the help of digital twin technology, Beijing has built a digital platform for the China International Services Trade Fair. The platform provides a comprehensive digitization and intelligent reconstruction resource for exhibition, forum, negotiation, trade and service scenarios. Creates panoramic reproductions of offline physical pavilions and provides online visitors with an immersive exhibition experience. It connects online and offline forums using 5G and breaks down geographical and language barriers through live video transmissions and intelligent translation. It is also building a cloud-based virtual meeting room that will fully merge the physical and digital worlds, creating a service fair that never ends. In 2020, the fair attracted a total of 148 countries and regions to participate online, with more than 20,000 companies and 188,000 people registered. Additionally, more than 5,300 companies set up online booths, and 550,000 online negotiations.

Beijing CBD Park uses digital twin technology to advance the development of a data element model

The management committee of the Beijing Central Business District (CBD) is building a digital twin spatio-temporal information management platform that will create a model data library for lower-cost reuse and data circulation by enterprises within the area, promoting the development of digital economy and innovation management. Currently, the CBD management committee has created an incentive mechanism to reward the enterprises for their investment in the construction of intelligent management platforms and digital scene applications. This mechanism effectively promotes the implementation of digital, networked and intelligent transformations using new technologies and helps boost the development of the digital economy.

Tianjin Binhai China

Digital twin which processes citizen’s requests in 15 minutes

Based on a three-dimensional map of the region, Tianjin Binhai has built a digital twin platform, which captures citizens' needs and desires in different ways and displays them in real time. The map also shows the entire government's response procedure. This platform breaks down the communication barrier between citizens and government and improves the efficiency of government services by logging and responding to people's requests within 15 minutes. At the period of the COVID-19 pandemic, 32,000 cases related to pandemic reports, resumption of work issues, etc. had been resolved. The completion rate was 100% and the public satisfaction rate was 94.5%.

Figure 28 New Area digital twin platform of Tianjin Binhai
Source: martearthproject.com

The DUET Project

Digital Urban European Twins is a project that change the way you see the city. Is an Innovation project that aims to leverage the advanced capabilities of Cloud and High Performance Computing (HPC) to make public sector decision-making more democratic and effective, by developing Digital Twins for policy exploration and experimentation across entire cities and regions. DUET will improve day-to-day city operations by helping managers respond quickly to real-time events and more easily harnessing the collective intelligence of all policy stakeholders to tackle complex, systemic policy issues that require innovative thinking to develop transformative solutions.[102] In order to take advantage of the increasing opportunities that vast amounts of city data offer to improve policy making, three main obstacles need to be overcome:

1. Lack of Access to Computing Power: Cities need cost - effective access to high computing power to creatively extract tangible benefits from large quantities of different data and enable real-time decision making.

2. Lack of Data Literacy: City data needs to be made easier for everyone to understand through simple interfaces that enable everyone to understand the issue being addressed and to be able to contribute ideas, own data and feedback towards creating a more sustainable future.

3. Lack of Data Ethics: As policy makers move towards using data from multiple sources, using new and creative data models, as well as advanced analytical techniques and user-friendly tools, it becomes increasingly important to ensure that the way the data is collected and used is not just the Personal Data protection requirements, but also to the broader ethical principles.

The true power of DUET which give it the chance to change the game is that:

Providing access to needed computing power: Real-time city management needs algorithms and computing power that can scale to distil oceans of open data, deliver insights and maintain efficiency. Cloud computing offers the ability for cities to access highly scalable hardware and software resources for the overwhelming majority of IT use cases. However, for future scenario predictions for policy modelling cities need to execute heavy algorithms and leverage near real-time deployment and processing require the use of high-performance computing (HPC). Cloud computing has not been used for high performance computing (HPC) to the same degree as other use cases for several reasons, namely cost, but DUET will advance this area by providing a new shared approach for its use in policy making and city management – using a Digital Twin. A “Digital Twin” is a new concept consisting of a continuously learning digital copy of real-world assets, systems and processes that can be queried for specific outcomes. DUET (Digital Urban European Twins) will consume Open Data and Data models from different sources in the city and integrate them with new technology capabilities including HPC, Artificial Intelligence and Advanced Analytics in order to provide a replica city environment where policy experimentation can safely take place. By predicting asset behavior and capacity to deliver on specific outcomes within given parameters and cost constraints, the Digital Twin provides a risk-free experimentation environment to inform stakeholders what they need to do with the assets in the real-word in order to both achieve the most effective long-term policy outcomes and short-term operational decisions.

In addition, DUET **Making data easier to understand**. Specifically it's easier to understand visualizations which are a critical factor for driving trust in using data for democratic decision making. However, most visualization platforms still need a degree of geo-expertise to truly use them to extract intelligence. DUET is different as it provides a 3D interface for its Digital Twins alongside a 2D offering. Users, regardless of their technical or academic background, will be able to walk through DUET's virtual 3D city neighborhoods and directly see dynamic data readings from multiple sources in a familiar context that makes them easy to understand. For example, users may see air quality through colors, traffic congestion as lines, incident sites as icons and so on. This simple, relatable way of viewing the city through multiple integrated data sources brings to life the tangible, systemic impacts of policy options, fueling 'what if' experimentation that unleashes creative and innovative qualities of all participants. This leveling of the field means that policy makers, administrative workers, emergency services, entrepreneurs, businesses and citizens can all participate in co- creation and consultation exercises as part of the traditional policy making cycle.

Establishing Ethical Principles for Data-Driven Decisions: The game-changing, cloud based, Digital Twin infrastructure with its deep-dive visualization platform for policy experimentation will boost collaboration and policy innovation and bring new discoveries and intelligence through novel views of the data. Using visualization tools, analysis of problems can have greater depth as many multi-disciplinary and multi-sectoral layers of data relating to the physical and social world can be considered together. Using a Digital Twin users can explore policy impacts across a whole city, rather than just one or two small localities. Instead of providing complicated graphs and multiple versions of maps from different industries to illustrate the impacts of, for example road routing decisions on mobility, air quality and health, the Digital Twin provides one version/replica of the city for all to use as a trusted baseline for exploring systemic impact of decisions. Visualizing multiple data sources through the Digital Twin make relationships more apparent, dependencies and interactions more clearly viewed and the trade-off between a variety of possible solutions can be modeled and evaluated.[104]

Three Main Objectives Of The Program

Innovation

Create a cloud and HPC enabled Digital Twin approach for collaborative policy making.

Experimentation

Test Digital Twin approach for more effective policy experimentation.

Sustainability

Ensure wider impact through the scalability and transferability of outcomes.

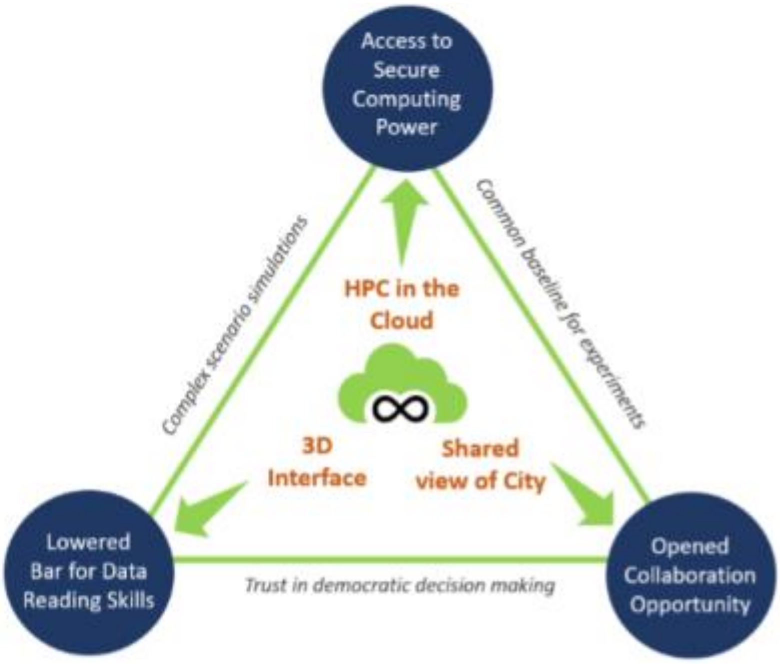


Figure 29 Duet's aims

Source: DUET Project, 2023, https://www.digitalurbantwins.com

Three Pilot Cities

Athens the large metropolitan

Athens is a metropolitan area that suffers from congestion and large surges of tourist inflows. The current challenge for Athens is to create an interactive pool of city data that will be dynamically updated, open, robust and usable for evidence-based decision making, enhancing the capital's attraction for locals and visitors. Athens therefore has a need for an integrated digital twin with the capacity to merge all of the city's data and make it easily accessible and useful for dealing with traffic and air pollution.

City's aims

- Embrace Digital Twin use to understand city relationships and overcome engagement barriers with stakeholders.

- Create new business value based on data-driven insights.
- Co-create digital services with the active engagement and participation of citizens.
- Improve effectiveness of policy design and implementation.

City of Pilsen

Pilsen is a mid-sized city in the western part of the Czech Republic. A hub for commuters, retail, entertainment and tourism, Pilsen is facing many challenges in terms of transport planning and urban development. Using both traditional and new data sources (e.g. crowd sourced data from mobile phones) to feed its digital twin, Pilsen wants to simulate different urban design scenarios (e.g., road construction, road closure) and measure their impact on quality of life over an extended period of time.

City’s aims

- Develop a set of tools dedicated for policy support in urban design including traffic and noise pollution modeling tools, visualization tools, a sensor data orchestrator and social media analytical tool.
- The visual insights will provide data-based evidence for policy making.

Region of Flanders

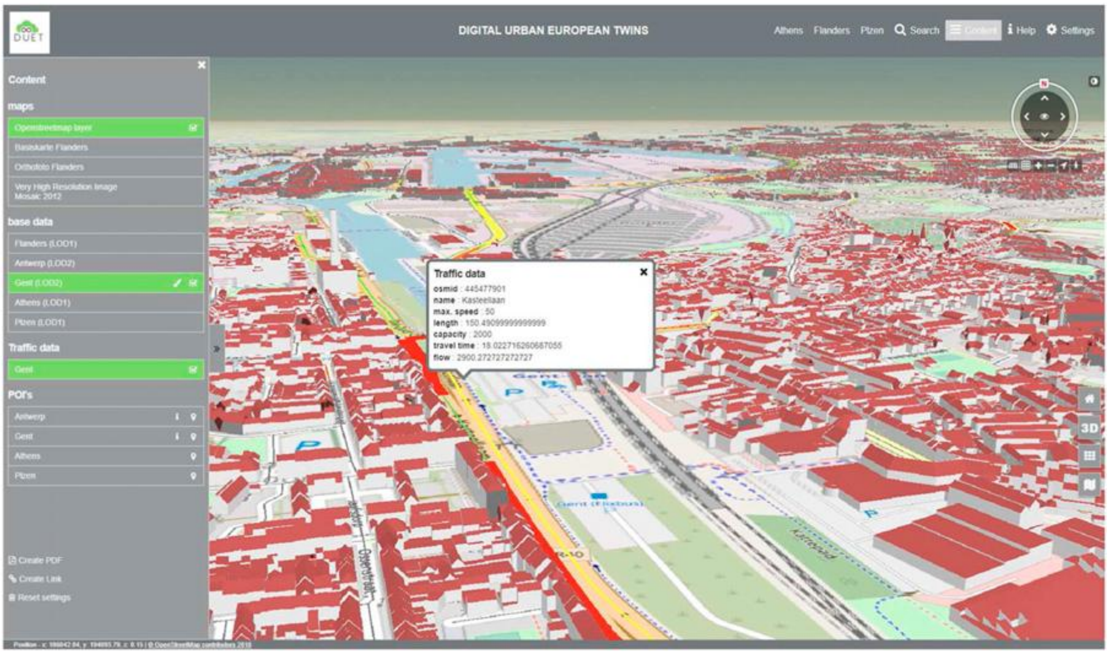
Flanders is an urbanized, densely populated region with a very busy road network. The slightest problem or the smallest accident during the rush hour can trigger very long tailbacks. No wonder the region is also a hot spot for air pollution. The DUET solution for Flanders helps to design, implement and evaluate new policy measures foreseen as part of the Flanders Regional Mobility Plan and the Flanders Environment Plan. The ultimate goal is to effect change that protects the environment and reduces negative impacts on human health. Leveraging traffic, air and noise models in the digital twin environment, DUET pilots explores, via the 3D interface, a range of what-if scenarios. For instance, what would be the impact on noise levels and air quality if the speed limit was lowered/increased on a given street? Making a street car-free can improve air quality and reduce noise levels, but what about adjacent areas - how will they be affected?

City’s aims

- Vision to create a Smart Region where everyone can access services and data.
- Cooperation between members of the society is encouraged.
- Citizens and companies become active in policy-making processes to improve the quality of

decision making and acceptance of the outcomes.

The (DUET) program develops and tests the use of Digital Twins through a web platform for better policy making. This is achieved through the use of data and machine learning models that allow the creation of digital copies (digital twins) of cities and by analyzing the correlations between vehicle traffic, air quality, noise and other urban factors. The participating Municipalities (Athens, Pilsen, Flanders) cover a range of scales to test different scenarios related to mobility, health and the environment. These areas have been selected for pilot purposes due to the immediate policy needs in all areas and the fact that these issues are often interrelated and interdependent, providing a unique opportunity to examine Digital Twins with multifaceted use of information and improved results for many sectors. The virtual copy created for Athens, our capital city used data from: measurements from air quality sensors, air pollution and its level, historical traffic data, geospatial data, boundaries of municipalities, areas and neighborhoods, traffic sensors on the streets of Attica and use of public transport. [103]



Traffic data
osmid : 445477901
name : Kasteellaan
max. speed : 50
length : 150.4909999999999
capacity : 2000
travel time : 18.022716260687056
flow : 2900.272727272727

Figure 30 DUET’s alpha version for Athens, Pilsen and Flanders
Source: DUET Project, 2023, https://www.digitalurbantwins.com/

Duet through the uses of urban scale Digital Twins, it explores the potentials of new strategies as far as low-emission logistics operations. Urban scale digital twins render possible the integration of data and the modeling of possible strategies, a wide variety of solutions for shared, connected and low-emission logistics operations. Among the parameters that the urban scale digital twins of the DUET project simulate ate those concerning different traffic, air and noise. Particular attention is paid to the exploration of traffic models, including static, dynamic and a local mobility (City flows) models. In order to simulate air quality data concerning traffic volume, road network, wind speed and wind direction are used. Despite the interest of the project to take into account how citizens perceive urban landscape, trying to render the urban scale Digital Twins ‘citizen-centric’, the efforts to ‘model citizens by looking at their emotional state’ entail risks given that they are based on significant abstraction and simplifications. While urban scale Digital Twins seem very efficient in simulating parameters related to sustainable environmental design, they are rather problematic when they intend to simulate ‘how people experience their built environment in order to develop smart cities in line with evolving patterns and preferences.

Below, we look more closely at the different traffic, air and noise models and how they can be used in the Digital Twin environment.

Traffic models

DUET experiments with three types of traffic models: static, dynamic and a local mobility (City flows) model. Models based on static or dynamic traffic assignment can provide a useful overview of traffic flows in a system and facilitate predictions based on alternate road network graphs or different demand patterns. This covers a wide range of scenarios that could be explored via digital twin, from simulating the effects of new developments, to assessing toll-induced deviations from routes on which they are levied, to simulating the impact of lane closures caused by construction works. Cityflows, on the other hand, uses different real-time data sources to better capture the multimodality of city traffic. Aggregating the signaling data, wifi scanning data, license plate recognition data, floating car data and citizen science data, among others, the City flows model is able to estimate traffic density per traffic type (i.e., motorized, pedestrian).

Air quality models

Air quality models use quantitative techniques to simulate physical and chemical processes that affect air pollutants as they disperse and react in the atmosphere. Within DUET, air quality model emissions will be calculated using data on traffic volume and road network, while considering other variables, such as wind speed and direction. Eventually, the model will be able to calculate dispersion of air pollution caused by traffic for a grid of spatially referenced calculation points. The results will be converted to map images using interpolation or heat map technology.

Noise emission models

The environmental noise is caused by industrial activities and different types of traffic. DUET’s intention is to create noise maps and various outputs necessary for calculating noise-exposure distributions with taking into account three different data sources - road traffic, rail traffic, industry. Since noise models can be displayed as maps in a digital twin, local authorities can use them to assess population exposure to noise generating activities, while considering other contextual factors.

Duet's Data sources

The tables below summarize and provide a full overview of the datasets, available data that have gathered during the presented research and represent significant opportunities for DUET and the three participating cities.

Athens Data Table

Dataset Title	Comment	Availability
Pollution Reduction and Environment & City Planning		
Environmental Data (Municipality of Athens)	Antennas in the city centre measuring temperature, PMI, humidity, air pollution	✓
Stores License (Municipality of Athens)	Data from license issuance on commercial stores provided by the City of Athens	✓
Controlled Parking System (DAEM)	Controlled Parking System for Athens: location of parking spots, duration of coverage, data of pre-reservation, economic data, spots reserved for residents, spots reserved for citizens with disabilities	✓
Pollution Measurement (Copernicus Programme)	Atmospheric measurements	✓
Air quality measurements (PANACEA)	Particulate concentration monitoring network by placing measurement stations in the major Greek urban centers	✓
Air-quality map (DRAXIS)	Air pollution data	✓
Ministry of Environment and Energy: Measurements of air pollution	YPEKA historical data on air quality (1984-2018)	✓
Ministry of Environment and Energy: Air Pollution Levels	YPEKA near real time Daily Report of Air Pollution Levels	✓
Air Visual: Air quality	Hourly update on air quality and air-pollution in Athens	✓
Urban Transport and Mobility		
OASA – Urban Transport	Public Buses Transport data: Locations of stations of Athens urban transport and timetables	✓
Urban Transport (OASA)	Public Buses Transport data: routes, number of passengers using public transportation	☒
Ministry of Transportation	Traffic data, data of accidents, traffic lights data, bicycle routes	☒
Region of Attica	Traffic data	☒
Social Media Data	e.g. Twitter, Facebook etc.	☒

Table 10 Athens Data Table for Duet Project

Pilsen Data Table

Dataset Title	Comment	Availability
Health and environment data		
Air quality sensor data	6 air quality sensors installed in the city, data owned by the city	✓
Air Quality report	Air quality measurements from the Czech Hydro meteorological Institute	✓
Traffic detectors	Data from 1000 magnetic loop detectors available through API and visualized in an analytical Map of Traffic (created in PoliVisu), owned by the city	✓
Traffic model	Traffic model data + traffic modeler backend and web application for real-time traffic modeling, owned by the city	✓
City’s Noise map	Noise model data owned by Ministry of Health	✓
Noise Action plan for main transit roads in Pilsen (Ministry of Transport)	Noise Action plan for main transit roads in Pilsen	✓
3D noise data	3D noise visualization in Pilsen, a result of a diploma thesis at UWB	✓
Heating source of buildings	Heating type/source for all buildings in Pilsen	✓
Pollution generators	Factories, waste incinerator, heat plant etc. owned by Czech Hydro meteorological Institute.	✓
Energy policy	Information on heating energy sources, data owned by the city	✓
Sustainability plan for Pilsen mobility	Long term investment strategy for urban mobility, with more than 80 measures	✓
Public transport routes	Vector data layer with public transport routes mapped to the street network of the city	✓
Public transport stops	Point data layer with public transport stops	✓
Crowd sourcing data on air quality/noise	Mobile apps, citizen science sensors at home etc. The city has its own LoRa network for IoT devices and also been covered by 5G as one of the first cities in CZ	✓
Real-time position of public transport vehicles	Pilsen Public Transport Company (PMDP) has the authority to make the arrangements. Normally shall be available late 2022 or in the first half of 2023.	☒
Amounts of public transport passengers	Availability not clear at the moment, needs to be discussed with the Pilsen Public Transport Company.	☒
Urban planning data		

Digital technical map	Technical infrastructure, pipes, energy and water networks etc., managed by the Pilsen Region, available to the city	✓
Cadastre (national register)	Ownership of land and buildings, managed by the Czech Cadastre	✓
RUIAN (national register)	Information on buildings - no. of floors, heating, energy sources etc., managed by the Czech Cadastre	✓
Pilsen GIS data	Information on buildings - no. of floors, heating, energy sources etc., managed by the Czech Cadastre	✓
Pilsen GIS data	All GIS datasets managed by the city	✓
Pilsen Urban Plan (land use)	Land use regulation for the whole city, created and owned by the city	✓
3D City centre and ZOO	3D datasets of the City centre and ZOO	✓
3D model of the buildings	The new 3D data of the city shall be available late 2022 or in the first half of 2023. The public procurement is currently being prepared by the city.	☒
Digital surface model	The new 3D data of the city shall be available late 2022 or in the first half of 2023. The public procurement is currently being prepared by the city.	☒
Digital terrain model	The new 3D data of the city shall be available late 2022 or in the first half of 2023. The public procurement is currently being prepared by the city.	☒
Public engagement & co- creation data		
Pilsen Open data	All open data of the city available on the open data portal	✓

Table 11 Pilsen Data Table for Duet Project

Flanders Data Table

Dataset Title	Comment	Availability
Mobility data & Safety		
ANPR (**Automatic Number Plate Recognition**) technology to help detect, deter and disrupt criminal activity at a local, force, regional and national level. Data collected from Federal police platform	Belgian Federal police allow access from the central police platform.	✓
ANPR data - Local sources (nonpolice)	Allowed, if conform GDPR - Extensive dataset (resource intensive)	✓
Road accident data	There is an agreement with the Federal police to use the data for the Duet project.	✓
Mobility data		
Parking data (on street and public parking spaces)	There is an agreement with the Cities Municipalities to use the data for the Duet project.	✓
Safety data		
Geospatial referenced register of installed cameras on public domain	There are agreements with the local police of its city. However a Flanders wide dataset is considered as difficult to be gathered.	☒
Crime and infringements geospatial register	There are agreements with the local police of its city. However a Flanders wide dataset is considered as difficult to be gathered. The main constraint regards if its in line with the Federal Police law.	☒

Table 12 Flanders Data Table for Duet Project

Duet’s Challenges & Opportunities

In digital smart city twins, not only air, traffic or noise can be modeled. Understanding how people experience their environment can be used by policy makers to develop smart cities in line with evolving patterns and preferences. If implemented correctly, emotional mapping can help a smart city become more inclusive by considering the true wellbeing of citizens. There is a growing number of use cases where emotional mapping is combined with passenger behavioral data to inform airport design. A similar approach can be applied to railway stations, stadiums, department stores and various public places like museums etc. Using biometric data, pedestrian models and other tracking technologies, it is possible to create a human-centric digital twin that acts as a real-time replica of citizens and their interaction with the environment. Integrating a human-centric component into a digital twin architecture means that the impact of even small changes on the user experience can be assessed much earlier. While such applications have certain benefits for operational and long-term planning, they inevitably raise no small amount of ethical concerns due to the nature of the data involved. For example, biometric data can reveal the identity of people based on certain distinguishing features. Likewise, if poorly designed, video surveillance systems can encroach on fundamental rights while creating a false sense of security. When developing citizen-centric digital twins, it is important to align with privacy and security best practices such as the EU General Data Protection Regulation (GDPR). Although in DUET’s example the team don’t plan to use any biometric data to make the Digital Twins compliant with the GDPR, they linked a data stream within the system with its owner. Such dynamic consent management enabled citizens to give or revoke consent from any service that uses their data. The reason was the research to provide a better coverage of air quality and traffic in a city. In addition discussions about the underlying smart city models and data should be held with citizens and other stakeholders from the communities. Collaboration is often a limited phenomenon to in projects like this and the few meetings yields limited sustainability. However Digital twins can make the collaboration a more long-lasting experience. As city dynamics are visualized, digital twins can coalesce stakeholders around common problems, encouraging them to seek consensus, define a shared vision and co-create solutions before finally testing them for impact in a transparent manner. In this respect, Digital Twins act as civic tech that promotes participation to improve service delivery.

Existing Digital Twins Tools

DTs in smart cities need to combine 3D rendering, spatial modeling and physics-based simulations of models with data flows from sensors geographically distributed across various IoT devices installed in city. In this section some of the most popular DT-based software solutions which are available are presented.

Dassault Systèmes' 3DEXPERIENCE platform is used to create urban-scale DTs such as the Virtual Singapore project. It consists of several tools for designing and creating 3D models, creating and simulating DTs of objects and processes and intelligently managing information. It offers city planners a holistic opportunity to make the right decisions across all instances of time.[116]

With its Azure Digital Twins platform, Microsoft offers a Platform as a Service (PaaS) for creating knowledge graphs based on digital models of entire environments. The platform provides an open modeling language called Digital Twins Definition Language (DTDL) for defining the digital entities which represent the real assets. The Azure Digital Twin is used for the visualization of the live graph that represents the environment and is created by the models defined by DTDL. The graph can be connected to external resources to perform data processing and execute business logic. Live execution of Azure Digital Twins is synchronized with the IoT devices.[117]

Another platform looking to offer smart city Digital twin solutions is Hexagon's HxDR platform. HxDR is a Software as a Service (SaaS) platform primarily focused on providing the necessary tools and data for developing 3D recreations of urban environments. The platform contains a growing library of real cities in which DT has implemented. The software is designed to seamlessly combine heterogeneous input data from different sources such as laser scanners, aerial photography, mobile mapping data, indoor and outdoor terrestrial scan data. The user can drag and drop the relative 3D model file created by the reality capture software and HxDR's auto-mesh feature will perform the integration. However, this product mainly aims at the design and development of 3D models and not at the integration of IoT sensor data.

CityZenith's SmartWorldPro is another DT tool that enables the aggregation of Building Information Modeling (BIM), Geographic Information Systems (GIS) and IoT sensors in a 3D platform. The user can view all systems and all relevant data including design, legal, financial, energy, maintenance and safety information in a single dashboard. The platform offers users the ability to scale their applications from a single building to even thousands of buildings. CityZenith offers a range of services that support the implementation of an end-to-end solution. These services include 3D/4D baseline asset modeling, API integration and custom user interface development.

Another interesting approach is the one provided by 51WORLD and its DT City operating system called 51City OS-POS. It is an all-element scenario platform for virtual world integration and control. Therefore, it integrates information flows in different formats, such as surveillance streams, building information, relational databases and IoT sensors. In addition, it offers a visualization front end that can not only visualize complex data in real time, but also provide comparison results. 51EngineTools is a 3D modeling tool which converts the models to the correct format and performs error checking. Features from image data from remote sensors can be automatically extracted and used to generate urban features such as buildings and roads. In addition, 51WORLD offers customized solutions that include services such as traffic management, workforce and asset management and energy efficiency monitoring.[111]

Twin Builder is an ANSYS offering that creates 3D models of physical systems. Although the product is only intended to support the design, development and execution of simulation scenarios, it can be integrated into a live IoT platform and thus fed with real IoT sensor data. Twin Builder offers a variety of ready-made simulation models and embedded systems.[112]

Bentley Systems, one of the founders of the DUTs, has invested heavily in DT technologies. The iTwin platform is their main asset. It is an open, scalable cloud platform that provides APIs and services for building DT applications. The platform leverages design data from various modeling tools and creates a DT synchronized with data from heterogeneous sources. The visualization API allows the user to interact with iTwin in a web browser using Bentley's cloud services. In addition, the platform provides APIs for managing reality data in terms of secure storage and heterogeneity. It recently expanded to integrate with NVIDIA Omniverse to create a graphics pipeline for real-time, AI-enabled visualization of infrastructure assets. Another DT solution in Bentley Systems is OpenCities Planner, a DT city planning and visualization application.

The solution provided by Deloitte called Optimal Reality. Is a DT ability based on simulation techniques originally used in Formula 1 racing. The platform takes real-time data and creates a dynamic model that can be accessed through a single web portal. The product mainly focuses on providing insights into air traffic and road network and event scenarios.[113]

ESRI is a leading player in the GIS and spatial mapping software industry and has developed ArcGIS, a framework for developing and integrating DTs. It offers integration of GIS, reality capture and BIM data with real-time IoT feeds and AI algorithms. The ArcGIS platform is offered as a PaaS and includes data hosting and content management services. The user can create and manage new content using the tools and applications provided, or use native open-source APIs for custom mapping and building spatial applications that have access to platform data and services. Finally, all applications can interact with a set of ready-to-use location services (e.g. routing service, geocoding service, elevation service, etc.).

IES company has launched the Intelligent Communities Lifecycle (ICL) Digital Twin, which is a single platform that integrates 3D models with a physics-based simulation engine, in real-time data, and AI data algorithms. The platform scales from a single building to an entire city, delivering data-driven insights into energy, operations of the city, carbon emission and capital savings. It is based on a set of interconnected tools that share a common database.[114]

The manufacturing sector is undoubtedly one of the pioneers in adopting DT solutions. General Electric (GE) is following this trend closely, mainly by offering different solutions for different use cases. For modeling of components, critical assets or asset systems, the SmartSignal and Asset Performance Management (APM) solutions can be used to create a digital twin of an asset. Technologies of GE's can be used to provide a connected view of end-to-end live networks of assets identified as Network Digital Twins. In addition, the development and operation of a Process Digital Twin can identify the optimal process for manufacturing a product in a specific manufacturing environment. GE offers a fairly mature solution integrated with its Predix IoT platform.[114]

Following in the same footsteps, Siemens has built a strong position in the field of DTs in the manufacturing and process industries. The company's open cloud-based IoT platform called Mindspere is able to host DT applications and feed them with data from products, systems or factories. The platform is part of a larger portfolio of software, development environments, and services called Xcelarator.

Moving on a larger scale, Descartes Labs has introduced the first-ever cloud-based geospatial platform aimed at providing a DT of the physical world. The platform provides three fundamental components: the data refinery, which contains over 15 petabytes of geospatial data from public and private sources, the workbench, a Python-compatible modeling environment, and the applications, which are packaged analysis solutions that provide data analytics and combine visualizations. It thus enables forecasting functions for various application areas and industries such as mining, shipping, agriculture, energy and financial services.[115]

The table below illustrates the comparison between the various digital solution tools and applications described above in terms of key components such as pricing and availability, simulation capabilities, integration with IoT sensors, data management options and implemented applications. It is evident that developers already have a critical mass of software platforms available to implement DT-based solutions.

Table 13 Comparison of the DT tools and available solutions

DT Tools and Products	Pricing	3D Content Creation	Simulation	IoT Integration	Data Management	Applications/Prototypes
Dassault 3DEXPERIENCE	Commercial / Demo Available	Yes	Yes	Yes	Yes	Urban Planning (Singapore, Jaipur)
Azure Digital Twins	Commercial / Free Trial	No	Yes	Yes	Yes	Energy, comfort, monitoring of buildings, traffic/fleet management, Urban Planning
HxDR	Commercial	Ready 3D City Library	No	Yes	No	Energy, comfort, monitoring of buildings, Urban Planning
SmartWorldPro	Commercial (SaaS) / Demo Available	Support the import of various 3D data formats, Ready 3D City Library	No	Yes	No	Urban Planning (Amaravati) Energy comfort, monitoring of buildings
51City OS-POS	Free (Community Edition) / Commercial	Ready 3D City Libraries	Yes	Yes	Yes	Energy, comfort, monitoring of buildings (Jiangbei New District in Shanghai), Urban Planning. Water Management
ANSYS Twin Builder	Commercial	No	Yes	Third party platforms	No	Pollution Control
Bentley Systems iTwin OpenCities Planner	Commercial	Yes	Yes	Yes	Yes	Urban Planning (Helsinki, Dublin)
ESRI ArcGIS	Commercial / Free Trial	Yes	No	Yes	Yes	Urban Planning (Boston), Port Management (Rotterdam), Traffic, Mobility Management
IES Digital Twin	Commercial / Free Trial	Yes	Yes	Yes	Yes	Energy, comfort, monitoring of buildings (Singapore), Urban Planning
Siemens Digital Twin	Commercial	Yes	Yes	Yes	Yes	Urban Planning, Traffic, Mobility Management,
Descartes Labs	Commercial	No	No	No	Yes	Urban Planning
Zero Gravity	Commercial	Yes	No	Yes	No	Urban Planning, Traffic, Mobility Management, Energy Monitoring
Gl.-Predix IoT	Commercial	No	Yes	Yes	Yes	Infrastructure monitoring

Challenges and recommendations for the Digital Urban Twins

Urban areas face enormous challenges in meeting the housing, infrastructure, transport and energy needs of their urban population and are in dire need of new ideas and solutions. Society lack an objective and rational understanding of the digital twin and its possibilities are still being actively explored from different perspectives. Digital twin technology is still subject to rapid development and change. Relying on a single technical perspective risks forming a one-sided understanding. For example, if too much attention paid to 3D modelling and visualization of city components, while overlooking the equally and even more important simulation and virtual-real interaction capability available through digital twin technologies, this could result in an unbalanced development of the technology.

The development of digital urban twins is not only determined by supply, but also by demand. In promoting the construction of digital cities, there is too much focus on the fine rendering of city details through high-precision technology, while lacking in-depth analysis of application needs and goals. This could disrupt business cycles such as urban planning, construction, administration and services, reducing digital twin technology to a conspicuous but useless trinket.

The challenge of data governance and privacy issues

In case there are limited data collection capability of urban IoT sensors can lead to an insufficient depth of application. Uneven data collection capability, inability to effectively capture underlying key data, inconsistent multi-dimensional and multi-scale data collection, and uneven construction of IoT and other sensor devices can lead to urban digital twins becoming unefficient demonstrations. Furtherly, the application of real-time dynamic detection and twin interaction in urban scale will not be deep enough to realize the full potential of the technology.

Currently, while the digital urban twin is still in the development phase, there is no unified standard system for the standardized management of different urban multisource data. In practice, the development of it relies on solutions from different developers and has poor system interoperability. There is no unified consensus on its technical architecture or data access standards, which making it difficult to integrate, fusion and uniformly process data with leading to disadvantages such as poor data quality and insufficient governance effectiveness.

The centralized processing of huge amounts of data leads to an increased risk of data security breaches and data protection breaches. Data sources are extensive and data storage and processing is heavily concentrated in centralized institutions (e.g Intelligence Hub of the smart city). This can lead to crippling city operations in the face of cyberattacks. In addition, video data analysis involves the use of citizen’s private data, which can easily lead to privacy abuse if the data cannot be effectively anonymized or subjected to strict scrutiny by qualified authorities.

The challenge of resource and corporate sustainability

In order to accurately and fully understand the digital urban twin and to identify and unearth its practical path and development potential, the integration of experts and teams from multiple disciplines – such as city management, demand analysis, digital technology and algorithm modeling is an urgent matter. These experts must work on scientific and theoretical questions and jointly explore the patterns of twin virtual-real interaction. Currently, the digital urban twin is mainly dominated by IT, mapping and other professional practitioners. There is a significant need for interdisciplinary talent in algorithm modelling and business analysis. The digital urban twin includes multi-dimensional and cross-industry systems and there is an urgent need for professional knowledge bases and industrial models in various aspects of data, models and interaction. Many areas of city governance currently lack interoperable knowledge bases and industrial simulation models, which can hinder the development of the digital twin. The digital twin business model relies too much on governnance. The high research costs of the digital urban twin are difficult to translate into practical application benefits, so the governments became an important source of funding for the development of digital twin technologies. Waiting for the digital twin technology system to mature, there is an urgent need to attract the participation of a wider range of citizens, institutions and market players, to innovate the digital urban twin.

4.Digital twin enhancing e-governance

The implementation of the digital twin in e-governance services will become the future of public service delivery in smart cities. Significantly optimizing service delivery in public services holds promise as the digital twin can be leveraged to achieve shared value that can produce innovation and the creation of new knowledge. This chapter examines the concept of the digital twins in the context of e-governance for innovation management.

E-governance with digital twin is increasingly becoming an integral part of business or public value creation and can be managed as people and organizations expect a much higher value for their well-being associated with a better set of outcomes. Digital twin e-governance is no longer seen as a static web service, but as the next enabling platform to offer comprehensive digital advice for each and every user. The goal of the digital twins is to extract all digital activity processes of a user and to deeply analyze the macros of all e-services. When there are crucial questions or issues that need to be reported to the (physical) user, the digital twin presents options, solutions and recommendations based on the entire collected data continuum.

In terms of e-governance, a digital twin is a digital representation of an individual with the ability to deliver services such as e-Citizenship, e-Employment, e-Participation, e-Business, e-Commerce, e-Health, e-Learning, e-Regulation, e-Entertainment etc. with near real-time data and advanced analytics. Individuals will be able to make, improve, discover, anticipate and make better and faster decisions thanks to the digital twin. The aim of this chapter is to enable us to define priorities, processes and outcomes of e-governance services using digital twins to optimize public service delivery.

Why is the application of digital twins relevant for deployment in the delivery of e-governance services?

People can use the digital twin to monitor their extensive digital footprint including e-Learning, e-Health, e-Participation, e-Commerce and any digital data generated to preserve the value of their own data. Embedding a digital twin in e-governance services will surely give people access to near-real-time data to better understand themselves and improve their own performance. In addition, people with the digital twin can properly plan, develop and improve their skills and qualities. This is only possible if the digital twin is set up and operated using e-governance and infrastructure systems. The aim is to show the potential of e-governance with a digital twin, which makes it possible to improve public services and well-being. Essentially, the digital twin offers two main advantages. First, it can improve citizens' competence in using e-governance services and increase their participation in new knowledge creation and innovation processes. Second, it can be helpful to focus on a coherent digitization of processes for smarter delivery of public e-services.

E-governance and Digital Twin

The use of information and communication technology in public services aims to improve the delivery of public services and administration by integrating workflows and processes and expanding communication channels for citizen engagement and empowerment. There are three types of electronic interactions in e-governance efforts: government-to-government, government-to-business, and government-to-citizen. The government-to-citizen conceptual framework is based on four main dimensions: availability of online services, communications, infrastructure and human capabilities. These dimensions directly affect the efficiency of e-governance services. As already mentioned, DT technology is considered a cornerstone of Industry 4.0 due to its multiple advantages, such as the elimination of errors, uncertainties, inefficiencies and costs in any system or process. The Internet of Things (IoT), Artificial Intelligence (AI), Big Data, Simulation and Cloud Computing, among other technologies that make up the digital twin, have proliferated rapidly. In all digital twin applications, IoT is the primary technology. The IoT relies on sensors to collect data from real-world objects and create a digital model of the real-world object that can be analyzed, updated, and optimized. As a result, the flow of data through a system determines the value generated by the IoT, which then enables digital twin applications to connect a virtual representation to a physical object in real-time, allowing for regular updates. Over the next six years, the global market for DT is expected to grow at a rate of 58%, reaching approximately 50$ billions in 2026.

The digital twin has three basic functions: listening/observe, evaluating/analyze and generating solution/advice alternatives. Physical objects generate big data from smart mobile devices, sensors and all IoT-connected devices. The digital twin will listen, observe and receive the generated data to determine if the physical object is in good condition. From the data obtained, the digital twin uses AI and analytics to analyze potential problems that may arise in the near future so that preventive measures can be taken before they become problems. Simultaneously, the digital twin can also be a consulting tool for physical objects in order to make the necessary decisions. Thus, it can be seen that the communication process between physical objects and digital twins is transmitted in two directions.

Figure 31 Digital twin's functions

In the context of e-governance, it has been claimed that governments will be able to observe and predict non-measurable indicators from the physical world, allowing for a more holistic assessment. For example, a Digital Urban Twin can co-exist with traceable historical documents, a verifiable current state, and a predicted future state. Emerging as the primary engine of urban wisdom, the digital twin can help policymakers or decision makers create orderly urban governance. Citizen participation in urban governance processes and monitoring of governance measures is possible. The digital transformation of more and more components of the planning and decision-making processes is becoming clear, comprehensible and understandable. [110]

E-governance Digital Twin modeling

Further research is needed on the use of digital twins in e-governance, particularly from the perspective of users (citizens) to highlight decision-making, smart cities, game theory, integrated infrastructure and sustainable cities. All elements of physical data that exist in the real world are subject to the implementation of a digital twin. However, the implementation process involves cost, time and manpower, with limits on what we can do. As a result, the scope of the implemented objects is strongly determined by the purpose, scenario and retention data of the digital twin.

The digital twin has been seen not only as a pillar of rapid digital transformation, but also as a pillar of rapid innovation as a result of merging IoT, artificial intelligence, machine learning and analytics with a graphical and/or spatial representation to create simulation models that are capable of changing and evolving along with their physical counterparts. The digital twin constantly learns and updates itself using real-time data from sensors on the physical object to reflect operating, environmental and working conditions in near real-time. The figure below shows a digital twin scenario model focusing on the life cycle of e-governance services, in which the key principle of the industrial revolution 4.0. The aim is to highlight the interrelated, holistic and iterative aspects of the physical and digital ecosystems. The core concept of the digital twin enables discourse in knowledge-building communities beyond conventional patterns. The development of knowledge through digital transformation in the context of the Fourth Industrial Revolution is supported by public proposals that e-governance needs to restructure public service delivery and that e-governance initiatives should be part of broader reforms to break down boundaries and improve public performance to improve services. In the case of Smart City, the reliance on smart mobile devices is evident, as evidenced by rapidly changing smartphone usage as people spend more and more time online.

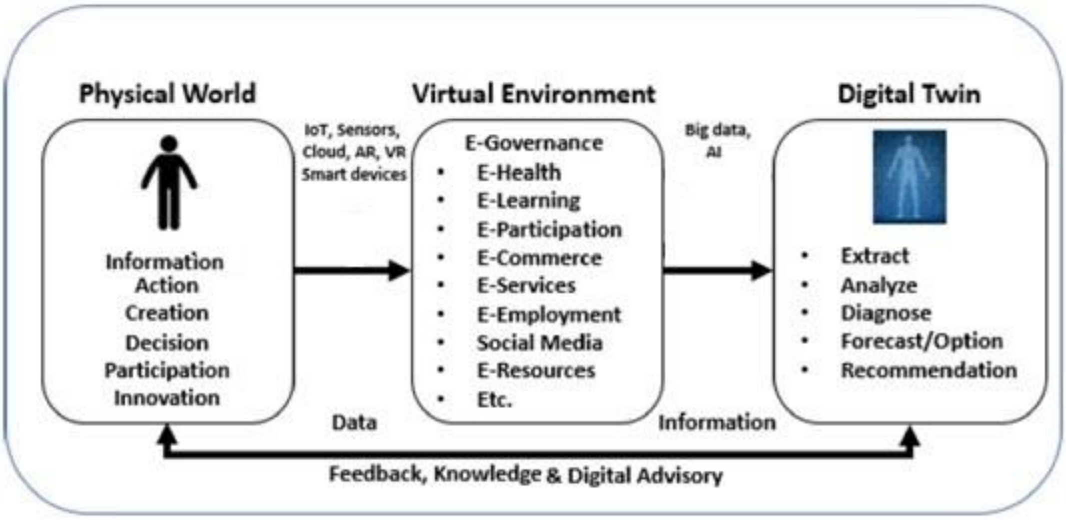


Figure 32 Model of digital twin scenario in e-governance

Compared to traditional e-governance services, data generated by individuals usually does not add much value. The data failed to produce integrated information comprising ideas, analysis, diagnosis, prediction or recommendation that can be transformed into knowledge for the development of new objects, inventions and solutions. Individuals alone cannot derive knowledge from their digital data generation. In the digital twin e-governance scenario, user data is integrated into a digital twin application when accessing e-governance services and other digital activities. Digital twin e-governance is becoming a centralized platform for individuals to expect much greater value for their well-being. It is evident that e-governance with digital twin will no longer be a static web service, but can fulfill a function as comprehensive digital advice for each individual user in a broader jurisdiction. The goal of the digital twins is to extract all digital activity processes of a user and analyze them thoroughly across all the e-services. The digital twin presents options, solutions and recommendations based on the entire collected data continuum when there are critical issues or issues that require attention and action from (physical) users. An example of the way how a digital twin respond to a situation in e-health system is that if a user has a minor health issue that is detected by their smartwatch and home health sensors, they automatically link the data to their system of e-health. The digital twin receives trigger messages from the e-health system. When the digital twin receives the messages, it uses AI and its expert system to assess the user's disease triggers and access all electronic resources. The digital twin then offers solutions or options based on its findings. Recommendations are offered to the user, e.g. Type of illness, an online doctor who can be reached promptly or what type of medicine should be taken immediately. The essence is the use of a digital twin in near real-time synchronization of data between physical and digital systems for problem prevention and response. Digital twin data integration can also provide users with commercial and financial advice based on the extraction of available e-commerce data and e-resources. Finally, data from the digital twin can be used on an individual level for planning and development. Individuals can visualize in real time how their well-being is evolving and improve their skills with the help of a digital twin. Based on progressive modeling, the forecast monitors the progress and determines corresponding tasks or activities based on the current status. Individuals can analyze alternative actions or options, measure their capabilities and calculate the resulting cost functions to determine the best course of action for the next task or activity. All of these could be done when e-governance adopts the digital twin for people.[112]

Synopsis

E-governance is expanding and will continue to grow as more advanced technology realizes its potential to prevent problems, reduce costs and time, improve efficiency, improve maintenance, facilitate accessibility, encourage new innovation and new knowledge and others goals that are still to be achieved. The application of the digital twin in e-governance is still in its infancy, which means there is still a long way to go to unleash its full potential. Identifying and addressing the challenges of the digital twin is crucial to maximize the use of innovation in e-governance services. E-governance can be seen as an ideal platform for the production and ownership of digital twins as it is aligned towards the goal of public interest, public empowerment and participation. However, without the commitment of the government as the initiator to collaborate with the citizens, the benefit of the digital twin would certainly be difficult to achieve. In order both service providers and individuals to share authority and control and assume a greater degree of self-involvement in the process, the digital twin requires philosophical and technological shift as user (citizen) generated data can be leveraged to achieve shared creation of value and to use for innovation and new knowledge development.

Suggestions for Governance

Both top-down and bottom-up actions are required to stimulate innovation. In order to promote the sustainable development of the digital twin in urban areas, strategic decisions must be made and guidelines must be formulated that move with the times. Local authorities and planning agencies should consider resource endowments, industrial specifics, cultural and religious backgrounds, geographic environment, and other broad factors when formulating a digital twin strategy and implementation plan. A recommendation for local governments is to set up an intelligent operation centre (IOC) to connect data resources distributed across different management units based on Big Data and system integration.[109] The center would play several roles snd uses such as situation monitoring, emergency control, display and reporting, process management and supportive decision making and it would serve as a decision center, early warning center, governance center, command center and display center with full-time management and internal coordination. In addition, a unified basis for digital twins should be built by attracting data contributions from commercial organizations and the online market via a cooperation model between government, business and academia. The structure of the digital basis should also be based on a hierarchical classification management system for databases and on relevant laws and regulations. The creation of a digital urban twin should be application-oriented, people-oriented and needs-oriented. Cities should not invest in building a digital urban twin for their own sake. Instead, the government should analyze the need for monitoring urban operational indicators and develop scenarios that take advantage of digital twin technology. Examples would be above and below ground space modeling (pipeline networks, planning and construction of energy facilities, etc.),analysis of scenarios with high risk (mines, forest fires, etc.), complex simulation and exercise scenarios with several topics (port dispatching, firefighting, emergency measures at major events etc.). Multi-layered life scenarios (e.g. citizens can apply for tailored services such as shopping, education and medical services via a single digital interface).

In conclusion, a pure technology mentality must be developed. A human-friendly and human-centric digital service system can only be built in the city if the tools respond to the needs of the population. In addition, private organizations should be encouraged to provide digital twin solutions and service products, which will then be applied in urban planning and construction management as they are developed.

Furthermore, a hierarchical data system for the digital twin must be set up to ensure a balance between data value and personal privacy. The government should pay attention to data ownership and protection of important data, and gradually establish a tiered and classified data resource system and a monitoring mechanism for data with different levels of accuracy and sensitivity. At the same time, data security and data protection strategies should be formulated depending on the priority level (e.g. contingency measures) and a security governance framework should be created that covers the entire life cycle of data. As a result, a friendly, safe and welcoming technology ecosystem can be built. Innovation is to be promoted through the joint integration of interdisciplinary expertise. In this direction, a multidisciplinary team for cooperation and innovation should be created. Based on existing digital twin project teams, urban planners, private technology companies, university algorithm designers, citizens and others could be invited to participate in the joint construction and sharing of digital twin technologies. Additionally through regular seminars and training courses on digital twins, experts from industry, academia and research institutes can participate together, examine and analyze the inner workings of urban development, publicize and promote digital twin concepts and practices, and help city managers to improve efficiency and effectiveness of their practices.

Simultaneously, there should be a focus on improving the digital literacy of citizens and the general public and gaining public participation in the construction and sharing of DUTs.

5. Outlooks and research directions for the Digital Urban Twins

Prognosis reffer that by 2050, 85% of the world's population is expected to live in cities. This means that in the following decades, urban centers will be even more confronted with problems such as energy supply, carbon emissions, mobility system planning, supply of raw materials and goods, and the provision of health and safety services for all residents in these fast-growing population centers.

To better respond to increasing volatility caused by climate change, pandemics, political and economic volatility, cities need to be transformed to increase their adaptability and resilience. Concepts and models for more livable cities must be created, in which digital technologies are the key elements for the sustainable development and organic growth.

Among other things, skepticism is emerging about pervasive digitization, the deployment of sensing, monitoring and visualization capabilities and other smart communication technologies used by both the private sector and governments. There are concerns of citizens about the processing of their data and therefore their privacy. The use of new technologies such as Artificial Intelligence, IOT, Sensors, etc., where personal data play a crucial role, faces increasing challenges and makes smart cities sustainable.

Artificial intelligence in the digital twins

While smart city activities and technologies have traditionally been about producing data and gaining new knowledge about a city's complexity and dynamics, AI is taking cities to the next step of using the data and knowledge to support decision-making. Urban AI is the use of artificial intelligence (AI) to improve urban planning, development, and management. With the increasing urbanization of the world's population, urban AI has become an important area of research and development.[123] AI is expected to enable smart city applications, among which urban mobility solutions, significantly contributing to resilience, sustainability, social welfare etc. AI applications in smart cities can be categorised in the following:

- **AI for governance** e.g.: Urban planning, disaster prevention and management.
- **AI for living and liveability, safety, security and healthcare** e.g.: Smart policing, personalised healthcare, noise and nuisance management and improved cyber security.
- **AI for education and citizen participation** e.g.: Locally accurate, validated and actionable knowledge supporting decision-making.
- **AI for economy** e.g.: Resource (cost and time) efficiency and improved competitiveness through, sharing services, efficient supply chains and customer tailored solutions.

- **AI for mobility and logisticse**.g.: Autonomous and sustainable mobility, smart routing and parking assistance, supply chain resiliency and traffic management.

- **AI for infrastructure** e.g.: Optimised infrastructure deployment, use and maintenance, including waste and water management, transportation, energy grids and urban lighting.

- **AI for the environment** e.g.: Biodiversity preservation, urban farming and air quality management.

Among other things, AI applications can improve and renew water and energy infrastructure, urban services, and foster empowered and resilient communities in smart cities. However, local governments, citizens and other smart city stakeholders face several challenges when it comes to implementing these applications.

Artificial Intelligence for future improvement of infrastructure in cities

Cities are facing major challenges to realize the acceleration of the energy transition. In order to achieve the climate goals and to accelerate the energy transition, extensive renovation etc., AI enables local governments, construction companies, utilities and other stakeholders to address these challenges. Artificial Intelligence has the potential to significantly improve the infrastructure of cities in various ways. AI can be used for the future improvement of infrastructure in cities such us:

Traffic management: AI-powered traffic management systems can help reduce traffic congestion and improve traffic flow. These systems can use real-time traffic data to optimize traffic light timings, manage traffic flow and provide commuters with real-time updates about traffic conditions.

Energy management: AI can be used to optimize the distribution of energy in cities. By analyzing energy usage patterns and predicting demand, AI can help energy providers manage their resources more efficiently and reduce waste.

Waste management: AI can also be used to improve waste management in cities. For example, AI-powered sensors can be placed in garbage bins to monitor their fill level and optimize waste collection routes, reducing the number of trucks on the road and lowering carbon emissions.

Public safety: AI-powered surveillance systems can help improve public safety in cities by monitoring for potential threats and alerting authorities in real-time. These systems can also be used to detect and respond to natural disasters, such as earthquakes and hurricanes.

Infrastructure maintenance: AI can be used to monitor and predict the maintenance needs of city infrastructure, such as bridges, roads, and buildings. By analyzing data from sensors and other sources, AI can help identify potential issues before they become critical, allowing for more efficient and cost-effective maintenance.

AI has the potential to revolutionize the way cities manage their infrastructure, making them safer, more efficient and more sustainable. However, it's important to note that the widespread adoption of AI in cities will require significant investment in both technology and infrastructure, as well as careful consideration of the ethical implications.

Artificial Intelligence for innovative and smart services in cities

Smart cities use innovative technologies to support and transform traditional networks and services. This section looks at two examples of smart services that can be enhanced by AI, namely smart city lighting and smart waste management. Smart urban lighting has often been seea as the solutionto initiate the development of smart cities. Combining improved and efficient public lighting through remote monitoring and control, lamp posts are an ideal object to equip with IoT devices which can collect, communicate and locally analyse data on traffic and pedestrian flows, environmental factors such as air quality, temperature, wind speed, humidity and urban noise. Innovative applications can be found in big cities like Barcelona, Copenhagen, Rotterdamm and others. In Barcelona, smart lighting infrastructure is deployed to monitor occupancy of beaches and public areas for crowd management.

The second example of innovative public services in a smart city is smart waste management, which includes the collection and processing of waste. By adding sensors on waste bins that measure how full, efficiencies can be realized through intelligent routing of collection according to how full, but also less inconvenience to citizens from full or broken bins. AI can be applied to predict the patterns of how, when and where waste is disposed of, opening up opportunities for city policy to encourage efficient waste generation and disposal among citizens. This innovation was implemented in the city of Rotterdam as part of the smart city project Ruggedized. Further efficiency gains are possible if AI-enabled autonomous vehicles are used for waste collection. In addition, AI can be used to optimize sustainable urban waste processing. In situations where waste sorting is not yet widespread in a city, computer vision can be used to separate waste streams for recycling towards a circular economy.

An AI software can take form of city's brain and be the central point of control for her e.g. for the maintenance of energy infrastructure, to AI applicable in multiple areas such as urban planning, health, safety and governance in an integrated and autonomous city. However, these are areas where human involvement is crucial in making choices between good and bad, sustainable and unsustainable, in short, ethical or unethical.

Artificial Intelligence for efficient urban mobility

Intelligent mobility solutions aim to increase safety and efficiency, reduce traffic congestion, improve air and noise pollution and reduce costs. Smart solutions for mobility are also seen as essential to further decarbonise the transport sector and achieve emission reduction targets. AI is a powerful emerging tool that has the potential to drive a sustainable transition towards more resource-efficient, livable and human-centric mobility systems, especially in urban contexts. AI applied to urban mobility can rely on data collected from existing infrastructures (e.g. traffic controller detection, urban centrals, video data, etc.), fleet data (car probe data, eBike fleets, public transports) and also third (public and private) party data. The public sector plays a crucial role in ensuring that the AI solution is inclusive and secure. Additionally, AI is relying on reliable, unbiased, fairly shared data, while still respecting the privacy of citizens. In particular, according to technology companies offering AI mobility solutions like Nokia, there is a need for neutral city networks to serve as the digital backbone for the smart cities, along with a neutral hosted data platform for building these new digital applications. Next-generation mobility is expected to transform automotive Original Equipment Manufacturers (OEMs), mobility service companies and cities. In addition, to be successful, these actors need to work together and also involve financial service providers, insurance companies, telecom and utility companies in order to achieve the common goal of new sustainable mobility. The shift towards AI-supported intelligent mobility will affect all value chains involved. Increased public spending on urban transit and growing incentives for entrepreneurial activities offering ridesharing and autonomous vehicles need to be complemented by data and AI related skills development.

Private initiatives for smart urban mobility

Electric cars companies provide users with an application to self-service book a car and select the rental period. Typically, these operators own charging and parking facilities in the area covered by the service. Self-service rental is often combined with a carpool option, underscoring the collaborative nature of the service. Regularly, the user is informed of the amount of CO^2 saved, which increases awareness of the environmental issue. Therefore, this AI-based intelligent mobility application offers social benefits. A French company named Clem'30 is active in more than 200 cities and is an example of offering this service.[125] Intelligent parking space management improves the accessibility and fluidity of parking spaces thanks to AI. In particular, parking management software enables the full integration of user spaces into the general mobility policy. Smart Parking Management enables, among other things, the management of different types of access rights by prioritizing certain categories of users, for example by function and means of transport. This application has a significant positive ecological impact, as it allows to anticipate a journey according to the availability of parking spaces and avoid endless wandering in search of a place to park. The applications mentioned enable a reduction in urban traffic and the environmental impact of urban mobility. Nevertheless, private vehicles are considered a sub-optimal sustainable solution for smart urban mobility, even if vehicles are electric, the risk of traffic growth remains.

Public initiatives for smart urban mobility

Dubai authorities boast a long list of smart mobility initiatives, including a bus-on-demand service, in select neighborhoods, the success of which was first demonstrated by a trial that looked at response time, transit time, passenger accessibility, affordability, comfort and safety were evaluated , residents' opinions and user experiences. They want to develop the futuristic transport system called Sky Pod. The Sky Pod is expected to reduce transportation costs by 44% and pollution by 12%. Among the excellences in smart mobility, Reykjavik stands out for the efficiency of its transportation systems. Copenhagen aims to become a zero-carbon city by 2025 through an integrated system that includes a smart bus priority system, fully electrified car sharing and building infrastructure to improve walking and cycling, including a network of 28 cycle highways. In addition, Geneva has a very efficient intelligent parking system, deployed through a network of sensors, which reduces the number of vehicles looking for a parking space by 30%.

Deployment challenges for local governments

In smart cities and urban mobility, every change is associated with costs. These costs are not necessarily distributed evenly and equitably among those who will benefit from the change, leading to conflicting interests that must be properly managed to achieve the intended improvement for all. These costs can be related to the technological paradigm shift and its societal acceptance. The introduction of AI for intelligent solutions in urban environments affects several established value chains in addition to end users. In addition, another category of challenges that typically arise for emerging technologies and related application areas concerns the creation of an appropriate regulatory framework. In terms of technological challenges, both AI-based smart city and urban mobility applications suffer from lack of computing power, trust, limited knowledge, biased data collection processes, and privacy and security issues, especially at the local level. The main existing barriers to the full deployment of smart cities and smart urban mobility solutions are related to the lack of understanding of the proposed solutions and the difficult access to them. The new breed of AI-based solutions, despite being machine-centric, must be a user-centric technology that understands and satisfies the human user, markets and society as a whole. For this transition to succeed, trust must be built and risk eliminated. Since the deployment of smart cities and smart urban mobility systems relies on similar technologies that need to be deployed in the same environment, local authorities face the same challenges for both. The table below provides a detailed overview of the challenges currently hindering urban smart solutions.

Challenge category	Description
Technological	**Increasing responsibility for citizens in local initiatives resulting in increasing the risks of mistakes due to lacking skills or due to incorrect information.** Need of verification and validation of information and stronger educational programs and publicly initiated guidance.
	Commercial pressure increase dependency on private parties as the developers and implementers of such services. As the algorithms mostly are (co)develop and the data they collect and the software and hardware they apply is often proprietary, this poses accountability and transparency challenges for (local) governments and smart city councils due to lacking information on the third parties involved.
	Lack of skills: AI related expertise is necessary for local governments to adequately assess internally or externally developed AI due to the implementation is often outsourced who providing tailored AI as a service and is necessery to control their trustworthiness and effectiveness.
	Technology, data availability and digital sovereignty The implementation and scaling up of AI applications in cities face the following challenges: ❖ Scarcity in technology, in computer chips for instance, can hamper the further roll-out and continuity of AI and IoT systems in smart cities. ❖ City-wide AI applications increase the computational requirements, to the point that high performance computing is necessary (supercomputers). ❖ Rise of dominance by Tech Giants (e.g. Nvidia), bringing interoperability and efficiency, but also dependence from these companies which makes the cost their toy. ❖ 93% of the AI adopters utilise cloud solutions with the cloud services marke dominated by firms (Amazon, Microsoft, Google, IBM) hosted in USA.
	AI quality and reliability: Missing or incomplete data and subpar accuracy and availability of data. This impacts the quality and trust in urban AI systems.
Social	**Ethical challenges in the utilisation of AI**. The utilisation of AI for and with citizens, centrally positioning the public values, requires local government to manage ethical challenges relating to conflicts of interests and bias in decision-making, economic pressure (in platforms, procurement), inequalities, privacy and data ownership and trust and transparency.
Regulatory	**AI systems in cities will increasingly work in an open, dynamic, hyperconnected environment.** Challenge of AI application is to integrate electricity, heat, water and mobility infrastructure.

Table 14 Overview of the challenges currently hampering urban smart solutions

Findings and recommendations

Urban AI is part of a larger stream of digital transformation in, social and digital realities. Effective and trustworthy urban-scale AI should be better explored in more programs addressing data sharing, communication networks, and mobility and energy policies, promoting capacity-building initiatives involving private and public individuals with a focus on local stakeholders. AI demands regulation across technology and domain boundaries. Furthermore, not all cities are equipped with the necessary expertise to ensure public values in digitization, resulting in them either not being involved as a local party or being unable to implement AI solutions implemented by commercial parties be adequately managed and controlled. When it comes to new regulation, the inescapable trade-off between efficiency and equity is crucial. In this regard, it is recommended to prioritize efficiency in order to accelerate the deployment of smart solutions in the urban context. This approach is considered socially acceptable, as even people without direct access to AI solutions will benefit from them thanks to positive externalities, including more efficient energy and waste management infrastructures, less pollution, noise and congestion. In parallel, fairness must be ensured through unbiased data collection. In addition, innovative procurement is to become the norm, which entails requirements for technically and ethically responsible AI.

Sensors and IoT devices for Sustainable Smart Cities

Advances in the use and implementation of sensors and Iot devices and their application for the development of smart cities will allow residents to access a better quality of life and play an important role in urban societies in genaral. The present part analyses the use of Sensors and Iot Devices in Cities important sectors.

Sensors for Health Monitoring

New technology of sensor technology in healthcare enables real-time monitoring of patients. Smart healthcare as its name is, provides services through smart devices (e.g. smartphones, smart watches, wireless smart blood glucose meter, etc.), through networks also (e.g. body area and wireless local area network) and provides various stakeholders (e.g. doctors, nurses, patient caregivers etc.) timely access to patient information and the ability to implement the right procedures and solutions, reducing medical errors and costs. Biosensors are an important tool when monitoring health and different applications of them can be identified in medical diagnoses and antigen detection among others. Inorganic flexible electronics have yielded relevant results including e-skin, epidermal electronics and eye cameras. Some common materials used to make these sensors are carbon-based or conductive organic polymers, which have poor linearity. However, more reliable and flexible sensors with lower cost, better linearity and faster response time have been created. New sensor developments create relevant opportunities in the healthcare sector. [131]

Sensors for Mobility Applications

Three main systems of urban mobility are vehicles, pedestrians and traffic. With the annual increase in the number of vehicles in urban settlements, congestion, pollution and traffic accidents also tend to increase. These problems indicate that there is an increasing need for intelligent mobility solutions. One such solution is intelligent traffic control designed to avoid traffic jams and optimize traffic flow. Due to repeated starts and stops, fuel consumption and CO^2 emissions increase in traffic jams. Therefore, providing solutions to congestion has a direct positive impact on urban mobility and air quality in cities. In addition, heavy commercial vehicles and freight transport release large amounts of CO^2 emissions into the atmosphere. The automotive industry has made significant efforts to develop more energy-efficient powertrains for hybrid electric vehicles, for example. However, most vehicles are still diesel powered and providing optimal solutions to reduce the CO^2 emissions generated by these types of vehicles must be a fundamental task.

Vehicles include several sensors that are required for their proper operation and measure several operating parameters of the vehicle, such as speed, energy consumption, atmospheric pressure, and ambient temperature. Such parameters are used to optimize speed profiles to minimize vehicle energy consumption, taking into account traffic conditions and geographic information. To achieve this goal, a cloud architecture is implemented that retrieves information from vehicle sensors and external services.

Virtual sensors have recently been used to improve innovative solutions, especially in the field of electromobility. Virtual sensors were introduced to operate in the sensor cloud platform as an abstraction of the physical devices. In particular, such a sensor can reproduce one or more physical sensors, facilitating and extending their functionalities and performing complex tasks that cannot be performed by physical sensors. Unlike a real sensor, the virtual sensor is equipped with an intelligent component based on a data processing algorithm to derive the required information processing the available input data from heterogeneous sources. In fact, virtual sensors are typically used in services where there is a need to derive data and information that is not available or directly measurable from physical sensor instruments. Although the use of such sensors has been researched in different areas of the smart city, they find a large application in the mobility sector. In electromobility, for example, they are used to predict the driver's personal mobility needs, estimate the duration and cost of battery charging, predict the energy demand of medium or long-distance journeys, etc. All these predictions are performed by ad hoc algorithms that take available input data from the electric vehicles, the users and the charging stations. [123]

Sensors for Security

The approaches for the safety of people and the environment are a very important part to achieve sustainable development in smart cities. Security is a state of being free from danger or threat and maintaining the stability of a system. Safety is a dynamic balance that consists in keeping the parameters that are important for the existence of the system within the permissible limits of the norm. According to the United Nations Human Security Handbook and the Sustainable Development Goals (SDGs) of the 2030 Agenda, the types of uncertainties that threaten the sustainable development of people and therefore the cities of the future are: food, cybersecurity, health, environment , personal, community, business and politics are the core of a smart city.

Food security

Quality and sustainable production involves intelligent hydroponic and gardening systems that gather information through sensors that measure pH, moisture, water and soil temperature, light intensity and humidity. Several methods are proposed to monitor food quality and safety during production and distribution, including gas sensor arrays to analyze chemical reactions that have occurred in spoiled food. Biosensors have also been reported in the context of food safety.

Cybersecurity

Design plane solutions are usually software-based and use diverse types of encryption techniques, including advanced encryption standard (AES) for crypto or level security and encryption, authentication, key management and pattern analysis for the system-level security.

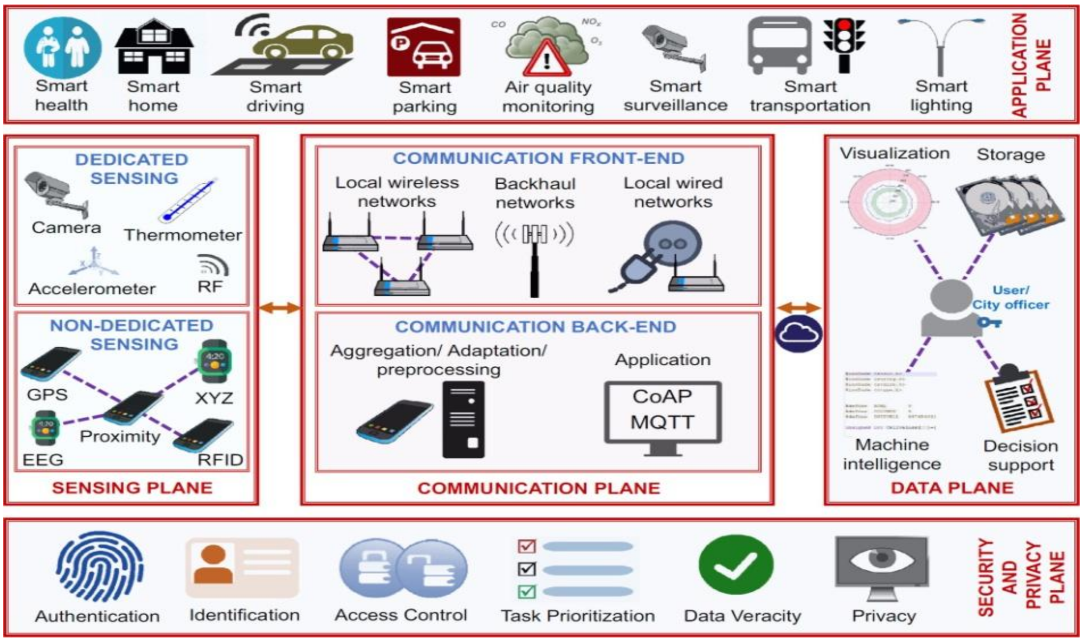


Figure 33 Smart city architecture defined in five planes

Source: Hadi Habibzadeh et al (2018) Sensing, communication and security planes: A new challenge for a smart city system design. DOI: 10.1016/j.comnet.2018.08.001

1) Application (connects city and citizens), 2) sensing (sensors measurements), 3) communication (cloud services), 4) data (processing and analysis) and 5) security and privacy planes (assurance of security and privacy).

Health security

Devices inserted into the body are designed to communicate with health centers and hospitals. The confidentiality, security and integrity of these sensors and health record information in relation to legal and moral issues are of great interest and importance.

Environmental security

The weather observation, disaster forecasting systems have increased dramatically. These tools are an integral part of the smart cities of the future. There is a wide range of sensors, including earthquake early warning systems that use vibration detection and monitor the earth's soil moisture and density, radiation level detectors, tsunami flooding forecasting methods that take seabed pressure data. These sensors are connected in a wireless network and provide a global forecast of environmental threats. Continuous Emissions Monitoring Systems (CEMS) enable better real-time tracking of power plant emissions to inform grid decarbonization strategies. Previous efforts to deploy low-cost sensor capabilities have resulted in fragmented data, but new optimization and AI tools are proposed to address this issue. New smart collection and visualization capabilities (e.g. satellite, etc.) focus on greenhouse gas emissions, forestry and other land uses (e.g. natural climate solutions).

Advanced monitoring, reporting and verification capabilities will continue to play an important role in enhancing the transparency and environmental integrity.

In terms of infrastructure and buildings, continuous monitoring to detect corrosion and minor damage to prevent a possible failure uses, among other things, the integration of surveillance cameras, humidity, atmospheric and stress sensors. A simple combination of vibration and tilt sensing devices provides one of the most inexpensive and highly efficient techniques proposed for a wide range of structures.[124]

Personal and community security

Biometrics and surveillance cameras are widely used to detect anomalies, violence and unauthorized actions. Smart lighting systems are a useful and inexpensive tool that uses common sensors such as light and motion detectors and can improve security tasks. Surveillance cameras, facial recognition systems and global positioning systems (GPS) combined with data processing systems are increasingly common tools in the hands of law enforcement as intelligent public safety.[131]

Sensors for Water Quality Monitoring

Water is an invaluable commodity and necessary for every living being. Smart water management mainly focuses on making water distribution systems more efficient by using sensors to measure and communicate. It applies in three broad areas: fresh water, waste water and agriculture. In addition, more holistic perspectives around shared resource systems such as the water-energy-food nexus will also benefit from new sensor capabilities and intelligent management systems enabled by digital technologies to provide more sustainable and resource-efficient use solutions. The main benefit of intelligent water systems is the remote control of valves and pumps with measurement of quality, pressure, flow and consumption. Consumption monitoring includes measurement and model applications to describe consumption patterns. Water loss management includes the detection of leaks. Water quality focuses on measuring, analyzing and maintaining a set of predefined parameters. It is an integral real-time management involving stakeholders. In agriculture, the use of IoT devices is a common way to make irrigation more efficient and effortless. Noise sensors and accelerometers are popular methods to detect leaks in water distribution infrastructure. The use of electromagnetic and ultrasonic flow meters and sensors to measure pressure are IoT technologies to analyze water consumption rate. Water quality analysis sensors are mainly used for physico-chemical parameters such as pH, temperature, electrical conductivity and dissolved oxygen. In addition, oxidation-reduction turbidity and the presence of toxic substances are important. Humidity sensors are used to measure soil moisture and help manage irrigation programs on agricultural land.

Figure 34 IoT sensor for water quality monitoring applications

Sensors for Waste Monitoring

Intelligent waste management consists in solving the inherent problems of collection and transportation, storage, separation and recycling of the waste generated. The use of smartbins refers to the implementation of various types of sensors in the bins used to collect waste, which provide quantitative and qualitative information about the contents of the bins. For the vehicle routing problem, the proposals are algorithms to optimize the routes considering social, environmental, economic factors, rush hours, infrastructure, type and capacity of collection vehicles and others to save resources like money, time, fuel and labor. An example, the My Waste Bin IoT container, is shown in the image below.

Figure 35 My Waste Bin, an IoT smart waste container, enabling real-time GPS tracking and weight monitoring

Sensors for Energy Efficiency

Energy is an essential resource for running the many activities that take place in cities. Therefore, the efficient use of this resource is paramount to reduce costs and promote environmental and economic sustainability. The main sinks of energy use in urban communities are those associated with industrial and transport activities, building operation and public lighting. Aiming on the sensors used to monitor the energy consumption of ground traffic in buildings and public lighting, it is confirmed that ground traffic is the main sink of energy use (45%) and therefore the main source of air pollutants in urban centres. Car manufacturers report the specific fuel consumption of their vehicles using laboratory test reports. However, they do not report this data for heavy-duty vehicles. In addition, the real energy consumption of the vehicle is influenced by human (driving), external (traffic, roads, weather conditions) and technological factors. Buildings account for 40% of all energy consumption and 30% of greenhouse gas emissions. The main physical and non-physical factors involved in indoor environmental quality (IEQ) are shown in Figure 36. These factors are measured using wireless sensors, virtual sensors and artificial neural networks. Public lighting systems account for almost 20% of global electricity consumption. Therefore, it is important to centralize street lighting control and intelligent management to reduce energy consumption, maintain maximum visual comfort and occupant demands. Neural networks, wireless sensors, algorithms and statistical methods are used to estimate energy consumption and the associated costs. Environmental factors, pedestrian flows, weather conditions and brightness levels affect light intensity. The urban space uses the most advanced information and ICT to support value-added services to manage public affairs and connect the city and its citizens while respecting their privacy.

Figure 36 Physical and non-physical factors in IEQ

Source: Yang Geng et al (2019), A review of operating performance in green buildings: Energy use, indoor environmental quality and occupant satisfaction

The variables influencing energy consumption in buildings and public lighting are usually monitored wirelessly. Various smart sensors such as artificial vision are used to measure temperature, relative humidity, electrical current, gas flow, air quality, lighting, luminosity, solar irradiance and acoustic emission. Smart sensors powered by the IoT are key to real-time monitoring of the many variables involved in energy management. These sensors can be adapted to virtual sensors. The main issue with wireless sensors is their battery life. Therefore, alternative sources of energy (heat, solar, wind, mechanical, etc.) are essential.[124]

Applications

In healthcare, sensors can be used in various areas such as: smart toilets, applications to monitor and control physical activity with the ultimate goal of rehabilitation or injury prevention, and applications in healthcare facilities. There are several methods of monitoring the condition of patients, for example: monitoring the electrical activity of the heart with a series of electrodes placed on the body, monitoring vital signs wirelessly for the tracking of the patient's location by reiciving alerts. Implementation of user-friendly interfaces to share information, based on wireless sensors. Implementation of an e-health monitoring system based on the fusion of multi-sensory data to predict activities and support the decision-making process about the person's health. All of these healthcare systems make it possible to monitor patients' activities and from their homes.

In mobility, the most common traffic reduction applications are related to accident detection and prevention, traffic incident identification, driving behavior investigation, and the application of real-time feedback. Interesting applications in urban mobility have also been suggested, such as intelligent traffic lights, intelligent parking, collision prediction and avoidance, vehicle detection and mobility visualization through heatmap representations. Heatmaps can also be obtained from the analysis of mobility data from vehicles and pedestrians, reflecting the behavior of various phenomena such as average speed in the city, location, frequency and duration of traffic jams.

For the water sector, by analyzing parameters such as soil moisture and nutrients, efficient irrigation programs can be developed, including remote or automatic irrigation systems, to reduce water and energy consumption. For example, a system like this allows real-time monitoring of water's quality of a river that crosses a city, or the implementation of a system that could be used in pipeline networks to monitor the quality of fresh water. Distribution systems must be regulated to ensure the required quantity and quality. Using sensors to collect real-time data can detect and locate leaks, which can affect a city's proper water supply or affect the infrastructure around the leak. Water distribution systems must be monitored to ensure the correct quality of water is being distributed and to detect contaminants.

In the waste area, the IoT system enables an onboard monitoring system that increases the problem reporting process and demonstrates good waste collection practices in real time. The use of mobile apps and software allows truck drivers to receive alerts from the smart bins that need attention and also get the optimal route to collect the garbage, reducing the hassle and cost of garbage collection. With the collection of information about the fill level of the bins, it is possible to determine the best types and sizes of bins, areas that require greater or special collection capacity, and when to collect. The sensors can enhance automation in identifying and separating waste, which can increase processing speed for reuse and recycling to transform a smart city into a zero-waste city. All the data collected from the bins and analytics, coupled with the use of a GPS to know the coordinate position of bins, dumps and fleet, can be used to manage the collection and separation of waste in a novel way.

Cities are trying to implement innovative technologies focused on minimizing energy consumption and improving the environment and well-being of their citizens. For this reason, there are various applications in the fields of buildings, public lighting and urban space such as counting, movement and location of people and vehicles, security measures for citizens, fire detection in buildings, smart homes and home networks, Light Emitted Diodes (LED) for wireless indoors and outdoor lighting, geothermal technology, hygrothermal comfort, cybernetic cities, ubiquitous connectivity, smart thermostats, indoor lighting apps, microgrids, structural health monitoring of buildings, green buildings and others.

Challenges and Opportunities

While the use of wireless sensor networks provides valuable data that can be used for better resource management, there is still room for improvement. Although different areas within the Smart City face specific challenges, a common opportunity is the development of new sensors and new approaches to the problem of detecting, preventing or anticipating the dangers that future Smart Cities may face. A major challenge in healthcare is the privacy and secure transmission of data. An example is a decentralized mobile healthcare system that uses verifiable patient attributes to perform an authentication process and preserve the attribute and identity. Inexpensive wireless sensor networks are helping to achieve direct communication between a user's mobile devices and wearable medical devices while enforcing privacy policies.

Intelligent transportation systems (ITS) are deployed in smart cities which has a positive impact on saving resources such as time and manpower, while reducing fuel consumption and emissions into the atmosphere. ITS image-based mobility applications are simple and inexpensive, but face reduced efficiency with lightning and weather changes. Another challenge is flexible traffic control, since collision avoidance systems, high-speed detection and data exchange are required. This information exchange process is vulnerable to security threats such as malicious attacks or data leaks. To meet these challenges, more reliable sensors and faster data transfer protocols need to be implemented.

Great efforts are made in smart security to detect, prevent or anticipate the dangers that smart cities' citizens and infrastructure may face. Security sensors show a tendency to improve the sensitivity, resolution and precision of current sensors. Almost all services in a smart city use digital data and rely entirely on the security and integrity of that data. Because of this, sensors must be hardened with effective security solutions such as cryptography and advanced self-protection techniques.

Smart water monitoring uses sensors to continuously and consistently measure water quantity and quality data. The data obtained can be processed and visualized in real time for end users or forecasts can be developed for water authorities. These technologies allow minimizing the risks associated with poor water quality and water supply deficiencies. Future sensors need to be improved in terms of cost and power consumption to withstand long measurement times without intervention and be resilient to adverse environmental conditions.

Waste management is vital in any city and targeting on a cleaner, tidier, and healthier living environment by using sensors and IoT technologies to improve waste management. Currently there are only sensors that can detect wet, dry or metallic garbage. However, it would be optimal to develop sensors that enable waste to be identified more precisely. For this reason, new sensors aimed at waste separation have to be developed and implemented. Separation is a key component in the waste management system as it allows much of the waste to be recycled or reused, resulting in a reduction in the amount of waste going to landfill.

Innovations in monitoring energy consumption in buildings, public lighting systems and urban spaces using ICT are an excellent option due to their adaptability. Important is the implementation of virtual sensors through Building Information Modeling (BIM), integrated with IoT devices to develop green buildings. Smart lighting systems with sensors that can be adjusted based on weather conditions, operating hours, and the presence of people or vehicles, with the streetlights serving as Wi-Fi connection points, allowing interconnected networks across the city area to monitor environmental quality and noise levels. Battery or energy consumption, high volume of data storage and security, durability and replacement, size, cost, installation and maintenance are the main shortcomings. Studies have suggested implementing energy efficiency monitoring using multi-mode sensors and low-power hardware systems. The implementation of low-cost sensors and the use of energy harvesting are the most attractive technologies for building sensors of the future. Artificial intelligence, big data and machine learning become essential due to the enormous amount of data collected and analyzed in the featured applications.

Photonics

Photonics enable much of the information and communication technology that makes cities smarter. In addition, it delivers advanced technologies to improve the quality of life for city dwellers. Photonics provides technologies that enable the growth of social networks, the Internet of Things (IOT) and infrastructure maintenance, among others. Conversely, smart cities offer applications for photonics and drive the advancement of future generations of materials, devices and systems. At the same time, data collected by sensor arrays in smart cities can be made available for immediate activation. In the context of smart cities, photonic sensors enable data collection from the environment, while communication technologies enable high-bandwidth connectivity between all smart city components. In addition, photonics provide lighting for cities, which affects all systems, operates around the clock and opens more and more completely new possibilities, such as energy-efficient vertical farming.

Current applications of photonics on Smart Cities

In the following paragraphes briefly reviewing examples of these application areas.

Smart lighting

The replacement of incandescent light bulbs for lighting and traffic control with light emitting diodes (LEDs) is an ongoing application of photonics. LEDs are much more energy efficient than older light sources. Several key applications of LEDs are human-centric lighting and vertical farming. The light levels around city dwellers affect their mood, productivity, sleep patterns and visual acuity. Human-centric lighting emerged to address the growing knowledge of the effects of lighting on human behavior. Case studies have shown improved learning among schoolchildren and increased patient satisfaction in hospitals when human-centric lighting replaced traditional, static indoor lighting conditions. Human-centric lighting requires dimmable light sources of different emission colors and was originally realized with fluorescent tubes. However, tunable and dimmable LEDs with an adaptive spectrum and superior performance have become the preferred light source. An additional benefit of LEDs for human-centric lighting is the potential on sensing and communication in networked lighting systems. Smart lighting is also important for lighting plants. Urban farming is the process of growing fruits and vegetables for human consumption in greenhouses in densely populated cities. The so-called vertical farms increase the crop yield per unit area compared to open, horizontal farming by replacing solar energy with artificial lighting. In addition, producing food in population centers reduces the transportation costs associated with importing food from rural areas. Using LEDs as the illumination source, the wavelength of the emission can be tailored for specific crops with heat generation and minimal pest attraction. [125]

Smart sensing

The rapid growth of urban areas has a direct impact on the environment, which in turn affects the health and well-being of city dwellers. Two important elements that are essential to humans and life in general are air and water. Photonics-based sensors play an essential role in monitoring and controlling air and water pollution. A range of sensors based on optical effects have been demonstrated to monitor air and water quality. In the urban environment, determining the air and water quality is a first step towards improving the quality of life of residents. Smart cities should strive to combine sensor modalities with integrated collection and decision-making processes to mitigate the source of pollutants in urban water and oxygen supplies.

Smart communications and signal processing

Because of its propagation speed, light is the physical medium of choice through which information is transmitted over long distances. Gradually, the importance of long distances has evolved as the miniaturization of optical components has enabled inexpensive optical links over ever shorter distances while the demand for bandwidth has increased. As internet traffic is increasingly dominated by data center activities, the need for cost-effective, compact, fast and efficient integrated optical components will increase. Fiber Optic Networks (FON) are already essential for running cities, enabling two-way communication between residents, businesses and the rest of the world. FON are intelligent systems that correct themselves when errors or failures occur in the network. Fiber-to-the-home (FTTH) is the final pillar of a FON and has become a critical component of smart cities. A smart city contains an extensive network of sensing and actuation nodes. Fast and efficient communication between nodes is essential for effective operation. FTTH offers the fastest communications links currently imaginable and is expected to become more widespread through interfaces to wireless communications and mobile platforms.[128]

Advanced photonic technologies for Smart Cities

Sensing and monitoring systems for smart cities have a continuous operating cycle: sensing - communication - decision making - sensing. Smart city requirements are inspiring the development of advanced photonic technologies such as detectors and sensors, light sources, modulators and optical hardware accelerators that offer unprecedented speeds for communication and decision-making while consuming little power in a small space. As the world population becomes more urban, photonics-based solutions are increasingly needed to improve the lives of all city dwellers.

During this research, data were gathered from the literature as regard with the implementations in Smart Cities around the world, for health, security, mobility, water, waste management and energy efficiency. These data are shown in the following tables.

City	Health	Security	Mobility	Water	Waste	Energy
Amsterdam	ICT in health, Health Lab					Clean energy generation
Rotterdam			Smart charging parkings	Thermal energy from waste water	Automated waste container measures and collection	New renewable energy sources (RES)
Glasgow			Electric Vehicle (EV)-charging hub battery storage in car parks			Intelligent LED street lights with integrated e-vehicle charging functionality
Helsinki			Car charging facilities		Automated waste collection	Smart grids
Tampere Finland			Smart transportation			
London			App for public transport		Smart Waste collection	
Milton Keynes England			Smart parking, MotionMap app		Sensors in recycling centers	Smart metering app
Vienna			Smart parking, car Sharing			Energy efficiency
Copenhagen			Bike lane	Water	Optimized	Energy

			network	qualityMonitoring	waste disposal	efficiency
Stockholm				Water management policies	Waste management system	
Paris	eHealth, smart medical records		Bike sharing, charging stations			
Geneva			Smart transportation			Fiber-optic, smart grid networks
Barcelona	Remote healthcare	Incident detectors at home	Traffic and public transport management		Smart Containers	Centralized heating/cooling
Santander			Smart Parking, GPS monitoring	Smart park irrigation		Smart public lighting
Malaga			Electric vehicles, charging stations			Smart grids, clean energies, smart lighting

Table 15 Implementations of Sensor and Iot Devices in cities of Europe

City	Health	Security	Mobility	Water	Waste	Energy
New York		Sensors deployment after 9/11 attacks				Energy efficiency using LEDs
Toronto			Smart urban zone growth			
Washington			Bike sharing, smart stations			Sensor-based LED streetlights
Seattle		Flood monitoring, law-enforcement cameras, gunshots GPS tracking	Smart trafic lights	Real-time precipitation monitoring		Reduction of CO^2 emissions
Medellin Colombia			Outdoor electric stairs and air wagons			
Rio de Janeiro Brasil		GPS/video monitoring installation in police cars	Traffic monitoring using cameras			

Table 16 Implementations of Sensor and Iot Devices in cities of North and South America

City	Health	Security	Mobility	Water	Waste	Energy
Singapore		Siren alerts for natural disasters	Traffic maps, public transport apps	Apps for water consumption tracking		Apps for energy consumption tracking
Hong Kong		Smart card IDs for citizens	Open, real-time traffic data		Smart waste management	
Shanghai			From Video Frames to Realistic Events			
Beijing			V2E solutions, smart cards for			

			transportation			
Songdo South Korea	Remote medical equipment and checkups		Self-charging electric vehicle technology		Underground waste suction system	Smart buildings
Seoul			Bus service based on data analytics			
Taiwan		Smart defense system for law enforcement				
Indonesia		Flood monitoring and report app				
Thailand		Tsunami and flood monitoring		Water management app		
India			Smart transport systems			Clean energy, green buildings

Table 17 Implementations of Sensor and Iot Devices in cities and countries of Asia

City	Health	Security	Mobility	Water	Waste	Energy
Adelaide			Wired communities			
Melbourne			Smart parking, open urban planning, metro Wi-Fi			Energy efficiency, smart grid, smart lighting
Sydney			ICTs in daily urban transport			
Perth		Cyber-security and digital forensics				
Brisbane			Pedestrian spines			

Table 18 Implementations of Sensor and Iot Devices in cities and countries of Australia

Section’s ending

Population growth and mobility into urban environments, it is clear that cities will face an ever-increasing demand to meet the needs of their citizens in the coming years. Different strategies have been implemented in cities on every continent to move towards smartness, to improve the management of their resources, to offer more efficient and trustworthy services, to improve the city's quality of life and to increase the engagement of government, science and citizens.

Continents such as Europe and Asia have the most reported smart city implementations, followed by the Americas, Oceania and Africa. High-income countries like the United States and China showcased a large number of smart city implementations. Although other continents and countries boast less smart cities, it is only a matter of time before more emerge. Several smart city sensor applications have been identified and described. In summary, most applications involved collecting and sharing data to provide on-demand services (medical records and examinations, city traffic, water and energy consumption), while others were aimed at improving the city's quality of life (citizen safety, green space management, water quality, waste disposal, public lighting). Among the major challenges in implementing smart cities, each sector has its own. However, common factors such as the improvement of sensors, massive implementations of data analytics (big data) and citizens' distrust of data sharing can be identified.

Future smart cities aim to ensure society and security through digitization and collaboration.For achieving security an internal motive for safe and ethical behavior must be created by promoting a culture of safety in the new digital environment. Finally, it is also important to keep in mind that in order to implement the proposed smart city solutions, collaboration with government agencies is essential. As well as a deep understanding of each implementation context and key links between sectors (e.g. transport, energy, energy, water, food, resource efficiency and recovery, etc.). In addition community engagement and involvement in the planning and exploitation of new technologies in urban infrastructure are essential, in order to improve policy feasibility, transparency, equity and financial sustainability.

As societies around the world begin to better understand how technological advances can improve quality of life and foster clean economic development, smarter communities will propel the future of cities toward a more livable, inclusive, zero-carbon and sustainable future.

Computing power (HPC, Cloud, Edge, Quantum)

High-Performance Computing (HPC)

Digital Urban Twins rely heavily on computing power. As the demand for DUTs grows, so does the need for more computing power. One way to increase computing power is the use High-Performance Computing (HPC) which plays a crucial role in the creation and operation of Digital Urban Twins.

One of the main challenges of creating Digital Urban Twins is the massive amount of data required to represent a complex urban environment accurately. HPC can process and analyze large volumes of data from various sources, including sensors, satellites, and social media, to create a comprehensive and accurate representation of the urban environment. HPC can also simulate the behavior of the urban environment, including transportation systems, energy consumption and air quality. These simulations can help urban planners and policymakers make informed decisions about the design, operation and management of the urban environment. Real-time simulations of Digital Urban Twins can also help in the management of urban emergencies, such as natural disasters or terrorist attacks. By simulating the potential impacts of such events, emergency responders can develop effective plans and strategies to mitigate the damage and save lives. Additionally, HPC can help in the optimization of urban systems, such as transportation and energy networks, to improve efficiency and reduce carbon emissions. These optimizations can help cities become more sustainable and resilient, reducing their environmental impact and enhancing their livability. HPC plays a critical role in the creation and operation of Digital Urban Twins. By processing and analyzing massive amounts of data and simulating the behavior of the urban environment, HPC can help urban planners and policymakers make informed decisions, manage emergencies and optimize urban systems for sustainability and resilience.

Cloud Computing

Cloud computing plays an essential role in the development and implementation of Digital Urban Twins. Some of the ways that cloud computing can be used are presented below.

- Data storage and processing: Digital Urban Twins require the storage and processing of massive amounts of data from various sources. Cloud computing provides scalable and flexible data storage and processing capabilities, allowing urban planners and researchers to easily store, manage and analyze large volumes of data.
- Collaboration and sharing: Cloud computing enables collaboration and sharing of data and resources between multiple stakeholders involved in the creation and operation of Digital Urban Twins. This can include urban planners, policymakers, researchers and citizens.
- Real-time monitoring and analysis: Cloud computing can facilitate real-time monitoring and analysis of data from sensors and other sources, enabling urban planners and operators to quickly respond to changes in the urban environment.
- Simulation and modeling: Cloud computing can provide the computing power required for running complex simulations and models of urban environments. This can help urban planners and policymakers make informed decisions about the design, operation, and management of the urban environment.
- Scalability and cost-efficiency: Cloud computing can provide cost-effective and scalable computing resources, enabling organizations to easily scale up or down their computing infrastructure based on their needs.

In summary, cloud computing plays a critical role in the development and implementation of Digital Urban Twins. By providing scalable and flexible data storage and processing capabilities, enabling collaboration and sharing, facilitating real-time monitoring and analysis, supporting simulation and modeling, and providing cost-effective and scalable computing resources, cloud computing can help urban planners and policymakers create more sustainable and livable cities.[127]

Edge computing

Edge computing is becoming increasingly important in the development and implementation of Digital Urban Twins. This new computing model refers to the processing of data at or near the source of the data, rather than sending the data to a centralized data center or cloud. Some of the advantages and future targets of this tenchology in DUTs are:

- Real-time processing: Edge computing can facilitate real-time processing of data from sensors and other sources in the urban environment. This can enable urban planners and operators to quickly respond to changes in the environment, such as traffic congestion, air pollution, or energy consumption.
- Reduced latency: By processing data locally, edge computing can reduce the latency or delay in processing data, enabling real-time response and decision-making.
- Bandwidth efficiency: Edge computing can reduce the amount of data that needs to be transmitted to a centralized data center or cloud, reducing bandwidth requirements and associated costs.
- Improved reliability: Edge computing can improve the reliability of Digital Urban Twins by enabling them to continue functioning even if there is a network outage or other disruption.
- Enhanced privacy and security: Edge computing can improve the privacy and security of Digital Urban Twins by keeping sensitive data closer to the source and reducing the risk of data breaches.

Edge Computing is becoming increasingly important in the development and implementation of Digital Urban Twins. By facilitating real-time processing, reducing latency and bandwidth requirements, improving reliability, enhancing privacy and security, the edge computing can help urban planners and policymakers create more responsive, resilient and secure cities.

Quantum computing

Quantum computing produces more benefits than classical computing. Is an emerging technology that has the potential to revolutionize the way of processing and analyzing data. While still in its infancy, quantum computing holds promise for solving some of the most complex problems in science, engineering and computing, including those related to Digital Urban Twins. Some potential applications and future solutions in Digital Urban Twins are listed below:

- Optimization: Quantum computing can help solve optimization problems, such as those related to urban transportation, energy consumption, and waste management. Quantum algorithms can help find the most efficient routes for transportation, reduce energy consumption in buildings and optimize waste collection routes.

- Simulation: Quantum computing can facilitate the simulation of complex systems, such as traffic flow, air quality, and weather patterns. Quantum simulations can help urban planners and policymakers make informed decisions about the design, operation and management of the urban environment.
- Cryptography: Quantum computing has the potential to break traditional cryptographic systems, which could pose a significant threat to the security and privacy of Digital Urban Twins. However, quantum cryptography can also provide a more secure alternative to traditional cryptography, enabling secure communication and data storage.
- Machine learning: Quantum computing can help accelerate the training of machine learning algorithms, enabling faster and more accurate predictions about urban environments. This can include predicting traffic flow, energy consumption and air quality.
- Big data analysis: Quantum computing can help process and analyze large volumes of data from various sources, including sensors, satellites and social media. This can help create a more comprehensive and accurate representation of the urban environment.

Quantum computing is an emerging technology with the potential to transform the development and implementation of Digital Urban Twins. By facilitating optimization, simulation, cryptography, machine learning, and big data analysis, quantum computing can help urban planners and policymakers create more sustainable, resilient and livable cities. [127]

More networking capacities (Beyond 5G)

The benefits of next generation mobile networks (5G, 6G, and beyond) are significant for urban societies. 5G could improve ongoing operations by continuously monitoring the real physical systems and use Big Data analytics and machine learning to predict any issues before they would happen in real world. The implementation and automation of IoT could benefit from 5G to reduce maintenance issues and optimize production. 5G is seen as an enabler for new emerging services including city management tool that could help the developing countries in addressing the critical challenges in terms of traffic control, water and sanitary management and urban security. This could be done by creating a DT containing the 3D model of the city and overlay the 5G network along with other information such as: transportation networks, street grids, buildings, IoT data, as well as people’s movements. Even though 5G is still being deployed, works are carried out towards defining the next 6G networks. The idea behind 6G is to enhance even further all the applications and vertical use cases of the 5G network by bringing the intelligence at the edge of the network.[129] Consequently, what lies beyond the 5G would be an intelligent interconnected system of DTs that enables the creation of a real-time digital world. Thus, 6G will be represented by connected and augmented intelligence that will change the way data is created, processed and consumed.

The Metaverse as a Virtual Form of Smart Cities

In the Metaverse, a Digital Urban Twin can provide a virtual representation of an urban area, allowing users to interact with it in a simulated environment. This can be used for a variety of purposes, including urban planning, transportation optimization, and emergency response simulations. Digital Twins in the Metaverse can help urban planners and city officials to test different scenarios and policies, and to make informed decisions about urban development, infrastructure investments, and resource allocation. Additionally, by integrating with other digital twins and data sources in the Metaverse, can enable more sophisticated simulations and modeling, allowing for more accurate predictions of urban trends and behavior. This can help to enhance the sustainability, safety, and overall quality of life in urban areas. Overall, Digital Twins in the Metaverse can provide a powerful tool for designing and managing the urban area of the future.

Metaverse is an extension of the “real” virtual world which is a complete simulation and mirror of the real world. The Metaverse is highly relevant for digital twins in urban contexts, as the use of digital twins in the Metaverse would bring greater expansions of communication and consequent benefits for society and nature. From how to manage infrastructure and systems to serve people, different services such as: energy, water, transport, to being able to intervene more effectively and connected with digital twins to serve citizens due to challenges at the systems level.

By allowing for real-time interaction, the Metaverse platform will further help DT technology to overcome barriers such as limitations in storage, processing, and updating capabilities of maps in real-time. This will be overcome as it will be possible to permanently store a digital replica of a physical object in the Metaverse such that it could be accessed anytime.

In cities, the concept of DT, especially within the context of the Metaverse will have unprecedented impacts on simulating and modelling events such as floods, bushfires, energy demands in view of changing urban population, traffic movements, climate change variables, and other pertinent concerns for the urban planning discipline. By creating a 3D DT of a city, or a landscape, it will be possible to predict the effects of different issues such as climate, traffic dynamics, energy production and consumption, among others, before they occur. Such prediction tools will inform decision-making about how to avert most negative impacts on urban activities and shift policy concentration upon the positive aspects.

There are already prospects of cities adopting DT technology to allow for real-time responses to different challenges affecting urban physical assets. For example reports that cities such as Orlando, Las Vegas, and Boston already have their virtual replicas, allowing local governments to anticipate and address different scenarios such as proposed land use, and impacts of new streets, among others. Such efforts could be positively complemented by the Metaverse where urban planners, developers, administrators, and other stakeholders will have equal opportunities to interact and collaborate within the digital realm as they make plans and seek solutions for various urban issues. For instance, regarding climate change, which is a major urban issue, the DT technology in the Metaverse will allow for both the prediction of such events as flooding as well as modelling prospective scenarios and this can inform infrastructure planning and emergency risk responses preparedness. Most importantly, the Metaverse could play a critical role in the reduction of emissions from sectors such transportation, manufacturing, and energy generation.

The development of the Metaverse is still in its early stages, and research in this area is in its infancy and fragmented along disciplinary lines, so there is little understanding of the actual opportunities and implications of this global platform. But what is certain is that the idea of the Metaverse has already raised serious concerns over the risks and impacts of its underlying core enabling technologies with respect to human, ethical, and social values.

Metaverse and Urban Governance

The prospect of the metaverse offers governments numerous possibilities for the future. In particular, this includes perspectives in tackling pressing urban challenges such as healthcare delivery (e.g. telemedicine), planning (e.g. modeling development proposals), and utilizing available urban spaces (e.g. attending social and musical events) as well as the creation of new employment opportunities, education, etc. in various fields. It's predicted that in the future, city governments will be able to manage activities like people registration and identity verification on virtual platforms without requiring a physical presence, and the Metaverse will make the whole process feel real and authentic. While the potential for urban governance in the Metaverse will be great, it will require significant investment and patience as the concept evolves. For local governments, the Metaverse will offer opportunities to improve interactions with residents, provide fast, efficient and real-time services, but also better manage assets such as urban spaces. It will also open up opportunities for new revenue streams, allowing local governments to undertake complex and capital-intensive projects. In addition, the Metaverse will provide local governments with opportunities to restructure existing urban planning models to include those that support human and social dimensions. Governance entities and various institutions including educational institutions, large corporations, etc. will take opportunities to carry out their activities in the virtual world in order to have better interactions with people and improve the quality of their products and services through the use of technologies like DT, which will enhace the

Metaverse. They will also have opportunities to explore other frontiers such as creating virtual products and service that will be available on demand as people try to improve their avatars, which are future commodities as the metaverse becomes more apparent. However, there are challenges and it is doubtful that the Metaverse will be able to address and overcome the common challenges of city management, including continuous negotiations and arguments, different interests and incentives, disagreements and fights, unpredictable decisions, inefficient collaboration, ineffective networks, and so on. The deployment of new forms of human collaboration through the use of advanced technologies must be geared to open governance processes. It will be important to engage governance structures at city and national levels to ensure that the Metaverse is not designed for purposes that would defeat the very purpose for which it is adopted. As with smart cities, improving governance requires the involvement of all stakeholders (public participation) with a decision-making structure based on approaches to provide more comprehensive and inclusive solutions.[130]

Towards Asimov’s Psycho-History: a prognosing for the Digital Urban Twin

Psychohistory: Using Big Data to predict the Future

Isaac Asimov science fiction writer and thinker introduced a concept called Psychohistory in his famous “Foundation trilogy” novel series. The Psychohistory combined history, sociology, and mathematical statistics to make general predictions about future events and behaviors of the human race, in the interstellar Galactic Empire in his stories. The use of this science only worked with large populations of individuals and for long periods of time. In addition, it could only handle a limited number of independent variables, it worked best when freedom of action was strongly restricted and only when its findings were kept secret.

Asimov used the analogy of a gas to explained it: an observer has great difficulty predicting the movement of a single molecule in a gas, but can predict the action of the mass of the gas with a high level of precision (kinetic theory).**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**

Obviously, this “science” is part of the science fiction realm but might be considered the first theory of using Big Data and Artificial Intelligence for prediction purposes. The central notion of psychohistory is still cited as both motivation and model for many contemporary attempts to leverage massive computing power and vast datasets for predictive ends.

Building up conclusions from Asimov’s Psychohistory, one could postulate several ways a Digital Urban Twin could be expanded, developing capabilities as the following:

1. Real-time remote monitoring and control: Generally, it is almost impossible to gain an in-depth

view of a very large system physically in real-time. A digital twin owing to its very nature can be accessible anywhere. The performance of the system can not only be monitored but also controlled remotely using feedback mechanisms.

2. Greater efficiency and safety: It is envisioned that digital twinning will enable greater autonomy with humans in the loop as and when required. This will ensure that the dangerous, dull and dirty jobs are allocated to robots with humans controlling them remotely. This way humans will be able to focus on more creative and innovative jobs.
3. Predictive maintenance and scheduling: A comprehensive digital twinning will ensure that multiple sensors monitoring the physical assets will be generating big data in real-time. Through a smart analysis of data, faults in the system can be detected much in advance. This will enable better scheduling of maintenance.
4. Scenario and risk assessment: A digital twin or to be more precise a digital sibling of the system will enable what-if analyses resulting in better risk assessment. It will be possible to perturb the system to synthesize unexpected scenarios and study the response of the system as well as the corresponding mitigation strategies. This kind of analysis without jeopardizing the real asset is only possible via a digital twin.
5. Better intra- and inter-team synergy and collaborations: With greater autonomy and all the information at a finger tip, teams can better utilize their time in improving synergies and collaborations leading to greater productivity.
6. More efficient and informed decision support system: Availability of quantitative data and advanced analytics in real-time will assist in more informed and faster decision makings.
7. Personalization of products and services: With detailed historical requirements, preferences of various stakeholders and evolving market trends and competitions, the demand of customized products and services are bound to increase. A digital twin in the context of factories of the future will enable faster and smoother gear shifts to account for changing needs.
8. Better documentation and communication: Readily available information in real-time combined with automated reporting will help keep stakeholders well informed thereby improving transparency.

6. Genaral Conclusions

Digital twins became a hot topic recently despite their enough years of existence. What started as a useful tool for engineers is now used by public administrations, racing teams and health practitioners, to give just a few examples. In smart cities, digital twins are starting to gain traction, driven by the proliferation of IoT infrastructures and data hubs, as well as advances in 3D modeling, AI and visualization techniques. Additionally, there are even more new scientific fields such as Photonics, Mobile Networks, Computing Power etc., which can be allies in the success of the Digital Twin technology. Given that cities are complex systems and as with any emerging technology, there are challenges must overcomed like technical, legal and cultural hurdles. For example, new skills must be brought in, new training infrastructure must be created, cultures and ways of thinking must change. Key risks in the current landscape will need to be considered, these include big data, security and economic returns. In addition, to clone every facet thereof by means of Digital Twins may be neither feasible nor practical. A better approach would be to apply the technology to key priority areas first and then scale over time. At higher levels, one can envisage a cluster of connected digital twins that optimize the performance of organizations and industries, even across borders. This in turn will require a common framework through which digital twins can communicate effectively and safely both with the physical environment and among themselves. Individual models are integrated through APIs to form a cloud of models that can be called upon to perform various what-if analyses related to traffic, air quality or noise pollution. The DUET framework is already deploying in three separate locations (Athens, Pilsen, Flanders). As well, there are many other research projects in cities around the world. As creatures of the IoT era, digital twins must implemented in strict privacy and security standards if they are to appeal to contemporary cities and citizens, many of which are becoming increasingly conscious of both cyber risks and their rights as data subjects. More over we need to consider data governance, open standards, APIs, privacy, intellectual property. Each organization, state or city will need to develop appropriate policies and practices. With the EU Generation Data Protection Regulation in place, are now legally bound to greater accountability and data collection must be planned accordingly. Location data, for example, is generally highly desirable and when properly collected can be a major aid in smart city planning and development, assinting governance also. Furtherly, given today’s shift toward more collaborative policy making, the amount of trust that digital twins command depends considerably on how relevant they are for citizens. Cities that build Digital Twins with only the interests of architects or urban planners in mind will miss out on the opportunity to engage the very people they are supposed to help. By contrast, Digital Twins that are accessible to the broader public are likely to be more sustainable and valued than those that cater to trained professionals only. So as it is well understood the collaboration and experience of the citizens is the base of the technology's success.

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Appendices

Appendix 1

Company or institution	**Perspectives**
Siemens AG, Germany	The Digital Twin Application Model contains three main elements - Digital Twin Products, Digital Twin Production and Digital Twin Performance - which form a complete solution system that includes existing Siemens products and systems such as PLM (Product Lifecycle Management).[137]
Dassault Systemes, France	Focusing on consistency of experience, consistency of principles, single source of data and macro-micro union between the digital twin and the physical entity.[133]
Ansell Asia Pacific, US	Digital twins include several elements such as numerical simulation tools, model scaling down techniques, auxiliary modeling languages and digital twin platforms.[137]
AEGIS Consulting Group, France	A successful digital twin should have five main elements: 1) clear goals 2) open data management in line with international standards 3) trust-building mechanisms 4) support for a changing city government and 5) a trusted digital twin operator.[134]
Deloitte	The six elements leading the evolution of the digital twin are: 1) simulation technology 2) new data sources 3) interoperability 4) instrumentation 5) visualization and 6) platforms.[135]
PwC	The digital twin system invovle infrastructure, connectivity networks, platforms, applications, data standards and management, security and privacy.[136]
CAICT	Covering various technical categories such as new mapping, geographic information, simulation, intelligent control and deep learning, the digital twin presents nine core capabilities: 1) IoT perception and manipulation 2) digital representation of all elements 3) visualization 4) data fusion and delivery 5) spatial analysis and computation 6) simulation and deduction 7) virtual-real interaction 8) self-learning and self-optimization and 9) crowdsourcing extensibility capabilities.[138]
Beijing University of Aeronautics and Astronautics	Proposed the five-dimensional model of the digital twin, composed of five elements: 1) physical entities 2) virtual entities 3) twin data 4) services and 5) connections.[139]
Tsinghua University	The three elements of the digital twin are: 1) data 2) models and 3) services.[140]

Table 19 Global research perspectives on digital twin elements

Appendix 2

Country	Summary
China	Improve the city information model platform and operation management service platform, build the city data resource system and promote the construction of a central city data resource. Explore the construction of digital twin cities.
US	From the perspective of the industrial internet, the definition of the digital twin, its business value, its architecture and the necessary foundations for its creation are explained, and the relationship between the industrial internet and the digital twin is described through practical use cases in different industries.
UK	Construct national-level digital twin values, standards, principles and roadmaps to unify standards for digital twin development across independent industries, enable efficient and secure data exchange between twins, unlock the value of data resource integration, and social and economic Aspects to optimize and environmental development methods.
Singapore	The Smart Nation and Digital Government Working Group, led directly by the Prime Minister's Office, clarifies national development priorities and establishes a national working group (SNDGO) to coordinate the implementation of Smart Nation 2025. Virtual Singapore, developed by NRF (National Research Foundation) in collaboration with Dassault Systèmes, includes static and real-time data to address issues such as urban energy use, waste management, community navigation, transport planning and disease transmission.

Table 20 Policies related to digital twins in major global economies