Digital Twins: Accelerating Digital Transformation in the Real Estate Industry

Mattia Santi

Abstract Digital twins have been introduced in 2002 at the University of Michigan by Michael Grieves. Digital twins are part of the Industry 4.0 revolution and are a strategic technology that, after being implemented in numerous industries such as aerospace and automotive, is now becoming important in the real estate sector. This chapter will introduce the concept of digital twins and their current applications, exploring different types of digital twins and their characteristics. The analysis will then focus on the existing issues facing the real estate sector, with an appreciation of how digital twins could significantly impact this industry. Digital twins will be explained covering the basic principles behind the technology. The chapter will continue analysing some contemporary applications of digital twins in the real estate industry developed by leading companies in the sector.

Keywords Digital twins · Building automation · AI and machine learning · BIM

United Nations' Sustainable Development Goals 9. Industry Innovation and Infrastructure · 11. Sustainable Cities and Communities

1 Introduction to Digital Twins

In recent years, digital twins have become increasingly popular and their use cases are spreading across all industries, from aviation to marketing, from automotive to real estate. Dr. Michael Grieves first introduced the concept of the digital twin in 2002 at the University of Michigan [1]. The concept presented was based on the idea of generating a digital clone of a physical entity and linking them together. Based on this concept, a digital twin can be defined as a digital clone of a physical system that covers its entire life cycle and is connected to it via real-time data exchange.

These data are analysed and visualized thanks to digital simulations and machine learning providing a real-time interconnection between the physical element and the

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digital element. This real-time connection makes it possible to analyse and understand the behaviour of the physical asset and provides useful insights to enable a predictive maintenance strategy (Fig. 1).

Dr. Michael Grieves, in his original formulation of the digital twin concept, describes a digital twin as a system consisting of two elements, the physical asset and the digital replica. In the model proposed by Dr. Grieves, these two elements are connected during the entire lifecycle of the physical asset, from creation to production, operation, and disposal. According to this model, the physical asset and its digital clone exchange data in real time providing feedback to each other in a sort of mirroring effect. The name of this conceptual model was the "Mirrored Space Model" [1].

A digital twin can describe a physical asset at different scales. To achieve a digital twin, it is necessary to have a physical asset, a system of sensors connected to this asset that collects data, a system that analyses this data in real-time and a system that helps visualise it. Therefore, the concept of a digital twin goes beyond the traditional notion of a visual model, if we consider for example a BIM model, the primary distinction between a BIM model and a digital twin is the connection between the physical item and the digital model via a feedback loop. The main scope of a digital twin is to monitor and manage an asset during its lifecycle, supporting the decision-making process and predictive maintenance.

Digital twins can be applied at different scales, for instance, there are digital twins representing individual assets or digital twins representing systems of multiple assets, therefore the level of detail adopted for the representation of the physical reality can vary based on the purpose of the digital twin. Digital twins can be used for different types of reasons and this affects the level of detail that needs to be achieved and the quality of data required to make sure that the information collected and analysed is suitable for the scope of the project. Considering that digital twins can collect and process large amounts of data in real-time, it is essential to use the appropriate level of detail required to achieve efficient and reliable digital twins.

A digital twin is characterized by three main elements: the data exchanged with the physical asset, the model and the visual representation of the model. Considering that the central idea is to establish a real-time connection between the physical and

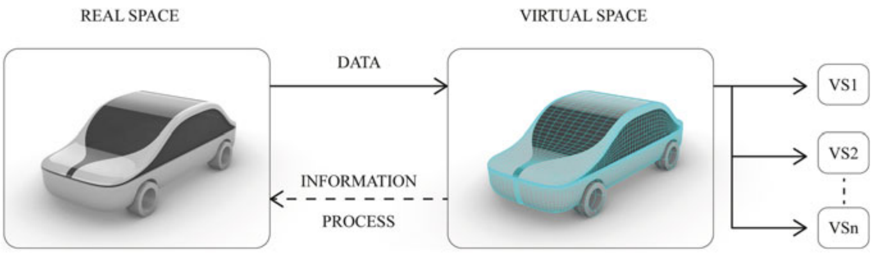

Fig. 1 Diagram reproducing the "Conceptual Ideal for PLM" introduced in 2002 by Dr. Michael Grieves

virtual realms, the data exchanged are defined as dynamic data, meaning data that can change asynchronously over time as soon as updated information is available.

Depending on the purpose of the digital twin, the model can be interpreted in a variety of ways. For instance, the models could be physics-based models to simulate the real context of the digital twin, agent-based models to simulate specific behaviours and interactions, or a combination of the two.

The other element to consider is the visualization of the digital twin model, the visualization strategy depends on the purpose of the digital twin but also the target users of the digital twin. For example, in some cases, a 2D visualisation may be sufficient, while in other cases a more immersive experience may be preferable. The correct visualization strategy is essential to allow the digital twin to absolve its main function of helping to make informed decisions.

Considering a wind turbine as an example, to build a digital twin to monitor this energy production infrastructure it is necessary to have sensors capable to measure in real-time the physical conditions of the turbine and its surrounding environment, such as temperature, wind speed, weather conditions, etc. In parallel, there should also be a digital model of the physical asset that contains the information needed to monitor the physical condition of the asset and its performance. In addition, there could be a 3D visualisation of the wind turbine that can help engineers observe its physical characteristics, its context and combine this information with the data received from the sensor to gain a multidimensional understanding of the asset and its performance, for example by measuring how much energy is produced and under what specific environmental conditions. More advanced models may also allow for simulation to test emergency scenarios and identify predictive maintenance strategies.

Digital twins should not be identified with simulation models. These are typically focused on simulating specific phenomena or processes. Although digital twins can also be used for simulation, digital twin models should be able, within their scope, to give a complete representation of an asset, allowing to run of multiple simulations in multiple scenarios. Another difference is that a digital twin establishes a two-way connection with a physical asset, allowing it to inform the simulation with real-time data collected by the interaction with the physical asset [2].

2 Origins of Digital Twins

Digital twins are a key technology in the context of Industry 4.0, although they are not a new technology. In fact, the idea of using digital twins was originally introduced by NASA in the 1960s and the Apollo 13 rescue mission in 1970 could be considered the first application of the idea of the digital twin, more than 30 years before the term "digital twin" was coined [2]. Each spacecraft was replicated in an earthbound version used to simulate and study the operation that the crew had to perform in space and to train the crew. The Apollo 13 simulators used the most advanced equipment in the entire space programme: only the crew and mission control consoles were real, while the rest was a simulation developed with advanced computers, complex calculations and expert engineers.

After the launch of the Apollo 13 spacecraft, there were technical problems and the mission changed from an exploration mission to a rescue mission. This became the first application of digital twins. NASA had a copy of Apollo 13 on the ground which enabled the engineers to carry out the necessary tests and make informed decisions to help the crew manoeuvre the damaged spacecraft to safety [3].

Contemporary digital twins are connected to physical assets through the use of the Internet and can exchange data in real time between the physical asset and the digital model. Apollo 13 did not have the "Internet of Things", but NASA was using state-of-the-art technology to achieve a near real-time connection with the crew 200,000 miles away. Considering this, Apollo 13 simulators could be considered early-stage instances of digital twins since they were connected to the actual asset in near real-time and could respond to changes in the physical asset [3] (Fig. 2).

This was the first application of digital twins before the term digital twin existed. Although Dr. Michael Grieves formally introduced the concept of a digital twin in 2002 under the name "Mirrored Space Model", it was actually in 1991 that the idea of a digital twin first appeared in the publication "Mirror Worlds: or the Day Software Puts the Universe in a Shoebox…How It Will Happen and What It Will Mean" by David Gelernter. The term "Digital Twin" (DT) first appeared in the draft version of NASA's technology roadmap in 2010. In this publication, NASA first introduces a formal definition of Digital Twin, describing it as "*an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best*

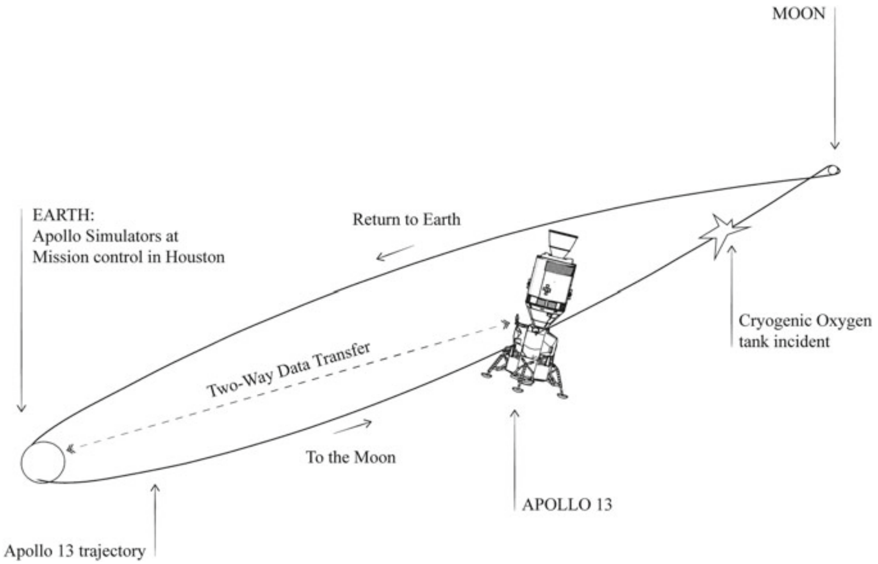

Fig. 2 Diagram describing the trajectory of the Apollo 13 mission

available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" [4].

A few years later, leading industry media such as Gartner, Lockheed Martin and Forbes recognised digital twins as a strategic technology trend. Until a few years ago, limitations in processing power, data scarcity, storage constraints, bandwidth costs, and technological hurdles slowed company adoption of digital twins, but we are now seeing digital twins expand across different industries. Digital twins are now within reach of many companies, supported by the quick integration of IoT devices.

Digital twins became a key technology part of the Industry 4.0 revolution, a new evolution of industry characterized by revolutionary technologies such as Quantum Computing, Spatial Computing, the Internet of Things (IoT), Artificial Intelligence (AI), Genetic Engineering, 3D printing and more. Digital twins can play an essential role in the Industry 4.0 landscape, helping to bridge the gap between the physical and digital worlds. Digital twins, depending on their implementation, may enable a completely new way of interacting with physical reality thanks to spatial computing and could open the way to a completely new range of services and business applications.

3 Different Types of Digital Twins

In several sectors, digital twins have been widely applied, helping to digitise different types of products. According to the type and the scale of their application, digital twins can be categorized into 4 different types: Component Twins, Asset Twins, System Twins, and Process Twins [2].

Starting from the smallest units that define a system, Component Twins are digital twins used to mirror the basic components of a product. The component twins allow monitoring of these individual system components, considering their operational status and performance.

Combining multiple components, a more complex digital twin can be obtained to simulate the overall behaviour of an asset, considering the interactions between individual components. This digital twin is focused on analysing the system at the product level and can provide a considerable amount of data considering complex interactions happening between multiple components.

Multiple assets create a system that can be identified as a System Twin. System Twins are useful for representing complex elements characterised by the interaction of multiple asset twins. They can be helpful when it is necessary to control a group of assets and study their interactions at a system level.

Lastly, process twins are used to study the interaction between multiple system twins. These are large-scale digital twins that operate at the macro level and focus on understanding how multiple complex systems interact with each other. For example, they can represent large industrial plants or entire cities [2].

4 Current Applications of Digital Twins

Digital twins aim to provide a real-time copy of a physical asset and require a combination of IoT sensors and software development to build a reliable digital twin.

Therefore, digital twins still require a considerable investment that currently limits the range of applications of digital twins. Despite this, digital twins are currently applied in several industries, for example, in power-generating equipment, which includes large-scale engines such as jet engines, locomotive engines and turbines for power generation, where digital twins are applied in the management of maintenance requirements. Buildings, infrastructures, and their systems are other important examples to consider, as they can all benefit from digital twin technologies from the design to the operational stages, allowing for the management of these assets while considering their spatial characteristics and the way users interact with them. Digital twins play an essential role in manufacturing processes, and they have a natural application in product life cycle management. Digital twins are also used in the healthcare business to assist in the creation of digital profiles for patients receiving healthcare services. Another possible application in this industry is the employment of digital twins by pharmaceutical firms to model genomic codes, physiological parameters, and patient lifestyles [2] (Fig. 3).

As previously mentioned, digital twins also find applications in the automotive industry.

Cars are complex assets with several interdependent systems, therefore digital twins play a crucial role in their coordination, maintenance, and customer care.

In the automobile industry, digital twins are also utilized in product testing, where the digital twin of a product aids in evaluating its quality and performance by conducting digital experiments with different compounds and raw materials to improve the design and maximize the product's performance.

Another important application in this industry is the development of self-driving cars, which requires the use of several sensors to comprehend the interaction between the vehicle and its surrounding environment. Digital twins are necessary to test numerous scenarios and imitate the behaviour of these vehicles in the digital world [2].

Digital twins also find wide applications in the aerospace industry. As previously mentioned, one of the first applications of digital twins was in the aerospace field with Apollo 13 and all subsequent applications developed by NASA. Today, digital twins are essential for monitoring and simulating the behaviour of mechanical components, complex systems, entire vehicles or vehicle systems. They are very important when predictive maintenance is required and in complex projects that require complex simulations and monitoring. For example, they are used to monitor jet engines to check the level of degradation and simulate engine behaviour under different conditions, informing maintenance and design strategies.

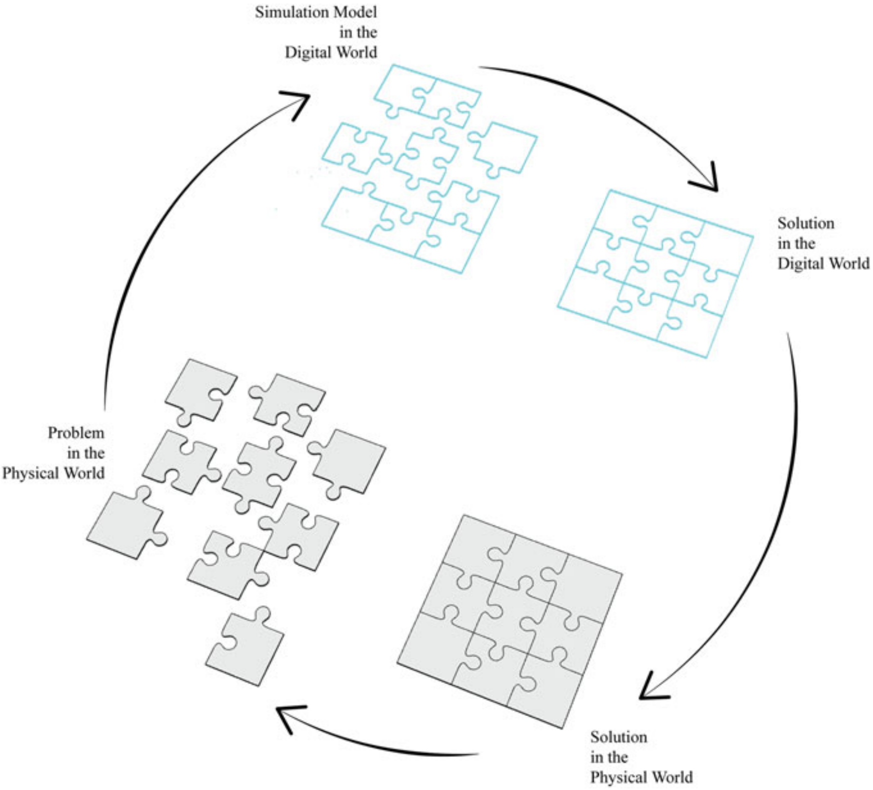

Fig. 3 Digital twins provide a risk-free environment to test new solutions

Digital twins can also play an important role in smart cities, where urban planning efforts can be guided by actual data to make better design decisions and simulate numerous scenarios to meet the needs of multiple stakeholders.

Digital twins are currently being applied at the urban level to simulate entire urban areas and to monitor traffic by extracting statistical information on public transport, pollution levels, traffic intensity, etc. Many of these projects are still in the initial stages and it is possible to imagine that the number of such applications will increase and that these projects will be further developed in the coming years [2].

4.1 Case Study: The Flying Catamarans

Digital twins are having an impact in several sectors and the sports industry is one of them. In 2012 the Emirates Team New Zealand (ETNZ) introduced new 72-foot hydrofoiling catamarans, which were subsequently adopted in the 36th America's Cup. In 2018, the America's Cup 75 Class Rule was published, defining the design rules for boats eligible to participate in the 36th America's Cup. No physical testing was authorized during the 36th America's Cup, therefore simulation-driven digital twins proved to be an essential design and testing tool. These racing yachts, rather than having a keel, have foil cant arms which can move outside or under the boat to provide stability and make these catamarans fly on top of the water [5] (Fig. 4).

These innovative racing yachts are 7.6-tonne boats with the crew, sailing at maximum speeds that can reach 50 knots, flying on the water, propelled by a double-sail skin mainsail, combined with a D-shaped mast to form a wing [5]. Since physical testing in wind tunnels or towing tanks was prohibited by AC75 class rules and teams could only build two racing boats, simulation-based digital twins became the solution for designing these racing yachts. The design team needed to create a comprehensive digital model that could be used by the entire team, from designers to boatbuilders and sailors, to create these high-performance products. To do this, they had to combine CAD tools with computational fluid dynamics (CFD), structural analysis and simulation, as well as product lifecycle management tools. The team's Velocity Prediction Program (VPP), which predicts boat speed under various conditions, is fed with CFD (Computational Fluid Dynamics) data from the simulation of many unique boat configurations characterised by different parameters, such as hull position or foil angles. This allows different design options to be evaluated against different scenarios and optimisation strategies to be defined. Another challenge in which digital simulation models have been important is the study of the interaction between aerodynamic and hydrodynamic forces operating on these vehicles. With the limitation of building only two physical models, having a digital twin of the vessel was essential to the entire design process, allowing for a high-fidelity copy of the physical asset on the one hand, and simulating the physical conditions in which the vehicle will operate on the other [6].

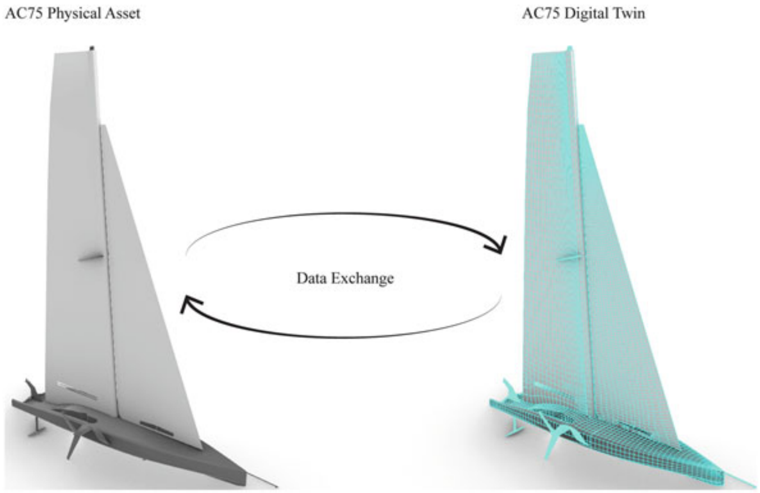

Fig. 4 Digital twins were adopted in the design of the AC75 racing yachts

4.2 Case Study: Digital Clones of the Earth

The function of digital twins as a predictive tool can be widely scaled, creating digital clones of complex systems like an entire planet. At the time of writing, there are multiple initiatives attempting to develop a digital twin of the Earth to monitor climate change using predictive models.

One of these projects is Nvidia's Earth-2 project, which aims to build a supercomputer to implement a digital twin of the Earth to study and predict climate change. The difficulty in predicting climate change is that, unlike weather forecasting, the period is too long and there are too many variables to consider. Designing the best strategies for reducing the effects of climate change and adapting to the changes requires climate models that can predict the climate in various places of the world over decades.

These models are "multidecade simulations" of multiple complex systems such as the atmosphere, oceans, land, human activities, etc. This level of simulation requires ultra-high-resolution climate modelling therefore this was not possible until a few years ago [7] (Fig. 5).

Another project that aims to create a digital twin of our planet is Destination Earth (DestinE), a project promoted by the European Commission in collaboration with partner organisations, which aims to develop an accurate digital model of the Earth that can collect real-time data and investigate how natural events and human behaviour interact.

The DestinE project is a complex system composed of three main elements, the "Core Service Platform", "the Data Lake", and the "Digital Twins". The "Core

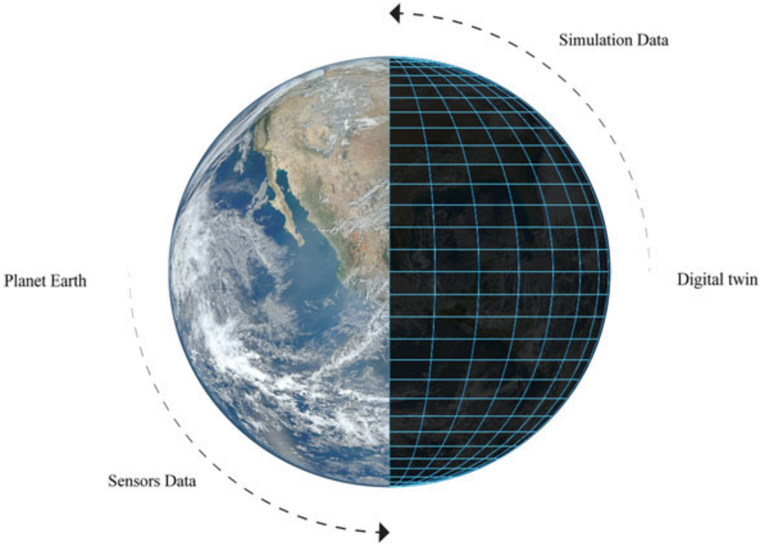

Fig. 5 The Destination Earth project intends to create a digital replica of the planet Earth

Service Platform" will be the platform and the interface for the users to access DestinE model. The "Data Lake" will be the pool of data collected by the data holdings provided by Copernicus the European Union's Earth observation programme, data holdings from ESA (European Space Agency), EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) and ECMWF (European Centre for Medium-Range Weather Forecasts) and additional data provided by various sources. Then the "Digital Twins" will be implemented to create digital clones of complex systems (e.g. oceans, lands, etc.) that will all be connected to the main model.

Through DestinE, users will have access to theme-related data, services, models, scenarios, simulations, forecasts, and visualisations. In order to produce accurate and useful scenario predictions, the underlying models and data will be regularly evaluated. DestinE initially will be accessible mainly by public authorities but in the future will be accessible also by a wider spectrum of users [8].

These case studies are some examples of how digital twin technology is currently being applied in different sectors. The implementation of this technology has advantages and disadvantages. Analysing the benefits first, the digital twins facilitate a more effective research and design process for product development and design. Indeed, because of the volume of data generated, they enable the prediction of an asset's performance and the potential of making essential changes prior to initiating the manufacturing process. This enables enterprises to obtain more accurate information and hence make more informed decisions more quickly. On the other hand, digital twins enable continuous monitoring of products and systems, resulting in a more effective product life cycle management process. Thus, digital twins can aid in addressing the difficulties of material resource scarcity, pollution, climate change consequences, and the transformation towards a net-zero greenhouse gas emissions economy.

The United Nations Sustainable Development Goals (SDG) serve as a framework for identifying objectives to address real-world problems that impact society and the environment. Regarding these goals, digital twins, especially when deployed as a large-scale digital twin network, can contribute to the achievement of several goals. For instance, regarding SDG 09 "Industry, Innovation and Infrastructure", digital twins can contribute to the development of robust systems to monitor infrastructure or production processes to maximize their resilience and efficiency. Regarding SDG 11 "Sustainable Cities and Communities", digital twins can help develop connected settlements with transparent access to information, facilitating participatory democracy through the inclusion of citizens in planning and policymaking, and promoting decarbonisation and resilience. Digital twins can help monitor and control energy use and its interaction with the distribution network in real-time, enabling the optimisation of resources, from individual products to buildings and cities.

On the other hand, deploying digital twins has some challenges, such as requiring the integration of several technologies, such as 3D models, sensors, data analysis, and machine learning, which need specialized knowledge and a significant initial financial investment. Several challenges are inexorably linked to technology: data privacy is one of them; sensors capture incredibly valuable data that must be managed and processed according to increasingly stringent cybersecurity standards. In addition, network partitioning and latency must be considered when designing these systems. Indeed, more processing power and bandwidth are required to maintain the service's real-time effectiveness as the system gathers more data and as more users interact with it. These are all aspects to be considered about this technology, regardless of the specific industrial applications.

The importance of digital twins in architecture and how they could change the real estate sector will be explored in the following paragraphs.

5 Current Challenges in Real Estate Industry

Digital twins can contribute to bringing innovation in Architecture providing solutions for some of the pain points currently affecting the real estate industry.

The digitisation of operations and data continues to be a significant challenge in the real estate industry. Existing buildings often have a history that spans several decades; thus, part of the information associated with these buildings is not available in digital format, and in other cases, is unavailable at all. Often, gathering data about buildings needs access to the facility's physical assets and human activities to extract data about the building. This makes it challenging to collect and maintain information on existing real estate assets [9].

The emergence of hybrid workspace models that blend remote and in-office employment is a prominent trend in the present real estate market. This necessitates the construction of more resilient working spaces that can adapt to a variety of usage circumstances and the provision of digital interaction with the physical area. For instance, it becomes crucial to provide a seamless experience that creates the same working conditions for remote and in-office workers and to ensure that all workers may access meetings even if they are not physically present in the office. On the other hand, it is essential to have digital and automated processes to maximize the use of space depending on user requirements, therefore creating spaces that can adapt to user demand [9].

Another challenge in the construction world is the need to innovate construction processes to reduce carbon emissions, improve health and safety, optimise the construction pipeline, and reduce costs and delays. The construction industry is currently characterised by the rising cost of raw materials, labour shortages and a decrease in the number of craftsmen available on the market [9].

Sustainability is a crucial challenge for the real estate industry; in 2021, 37% of global CO_2 emissions were due to the buildings and construction sector, which accounts for 34% of global energy demand [10]. Buildings are characterised by embodied carbon generated during the construction process and operational carbon emitted during the operational life of the building. It is difficult to monitor energy consumption, especially in existing assets, so it is important to incorporate IoT devices to monitor consumption and integrate circular models to reduce the carbon footprint of the building sector and develop optimisation strategies to improve building performance.

On the other hand, another challenge is the integration of IoT technologies in existing and new buildings. Implementing this technology would give the possibility to access building information remotely, an important element that becomes crucial when physical access to the asset is not possible. In this sense, Internet of Things (IoT) technologies, whether sensors or data systems, are essential to be able to gather information about the building in real time [9].

6 Digital Twins in Real Estate and Architecture, Engineering and Construction (AEC) Industry

Design, construction and management operations can be facilitated by the use of digital twins, as buildings are high-value assets with complex life cycles. Besides being physical assets, buildings are also environments where people live and work, building social relationships and forming communities. To further evaluate the possible uses of digital twins in the real estate sector, it is important to reflect on the profiles of users who may be interested in using this technology.

One of the first user profiles to be considered are professionals involved in the design of buildings, such as architects and engineers involved in the design process and in the decision-making. Architects and engineers could benefit from accessing data on the performance of the assets designed, to provide better ongoing support to clients and learn how to improve design services.

Social workers, for example, may be interested in determining the social impact of specific policies and may need to discover resources and solutions to give effective assistance to individuals. Asset owners are also user profiles to be considered. Digital twins could provide them with greater control over their assets and lower management expenses. Another profile is elected officials who determine and vote on how public funds are distributed and invested and who, thanks to the implementation of city-wide digital twins, can analyse and understand the real needs of citizens.

The policymaker profile should also be considered as they are in charge of recommending and establishing laws and norms. This user profile would unquestionably benefit from having access to structured facts to comprehend the impact of past actions and make educated decisions for the future. A crucial profile is that of an emergency service planner since they are responsible for gathering data and simulating the effects of emergencies. In addition, tourists can benefit from a connected ecosystem of digital twins, as they would be able to locate the information they want more easily thanks to the interaction and exchange of information with the built environment. Finally, numerous forms of digital twins might help small company owners to identify local patterns and make key choices about the services they supply.

Citizens, in general, could benefit from accessing digital twins of public spaces to learn more about their neighbourhoods and how they can contribute to improving their community and environment [11].

Reflecting now on the potential applications of digital twins in the real estate sector, one interesting application is to model and anticipate how tenants would use and interact with the property, gaining insights into users' comfort and productivity. In order to increase the user's comfort, a digital twin might monitor the environment and provide recommendations and adjustments. This ability to foresee allows more informed project choices and favours the development of successful management strategies. Digital twins, for instance, may be used to examine complex utilization scenarios for commercial and public buildings, enabling flexible day-to-day space and function configurations.

Another important area of application for the digital twin is the design process. In fact, with this technology, designers can create more than just a 3D model, they can create a sandbox environment for a project, an interactive game in which design ideas, products and user scenarios can be tested against multiple design iterations, different environmental conditions and environmental data. The construction process can be replicated and visualised using digital twins. Computational analysis is already widely used to improve the design and many organisations now have access to sophisticated methodologies that link different disciplines, but with digital twins, designers have more reliable information to test design ideas in different scenarios, using environmental data to make their studies context-specific (Fig. 6).

Considering that digital twins are able to store maintenance information and can enable the automation of part of the building maintenance process, they can also enable better maintenance strategies. Given the need to move towards a more sustainable use of energy, buildings will no longer rely solely on programmed responses but will be required to provide autonomous responses to different user behaviour and different environmental conditions to optimise system behaviour and the use of resources in real time.

Digital twins could become an important tool for studying strategies to improve the sustainability of buildings. It is possible to analyse a building's performance and calculate its carbon footprint in real time by collecting environmental data. This allows the implementation of methods to optimise a building's energy use and make it more energy efficient. Digital twins could be useful to identify waste streams and their potential as resources, increase operational efficiency and resource utilisation through waste reduction, quantify environmental expenditures to encourage a circular economy, and help achieve zero-emission targets.

Another interesting application of this technology is at the urban scale, where it is possible to create virtual clones of entire cities and neighbourhoods, allowing large amounts of data to be recorded and studied at the community level, providing crucial information for making informed decisions at the urban level. According to a study conducted by the C40 Cities Climate Leadership Group, urban policy decisions made before 2020 might affect up to one-third of the global carbon budget that has not yet been determined by past decisions [12]. Therefore, political decisions and public administrations play an important role in creating the conditions to achieve

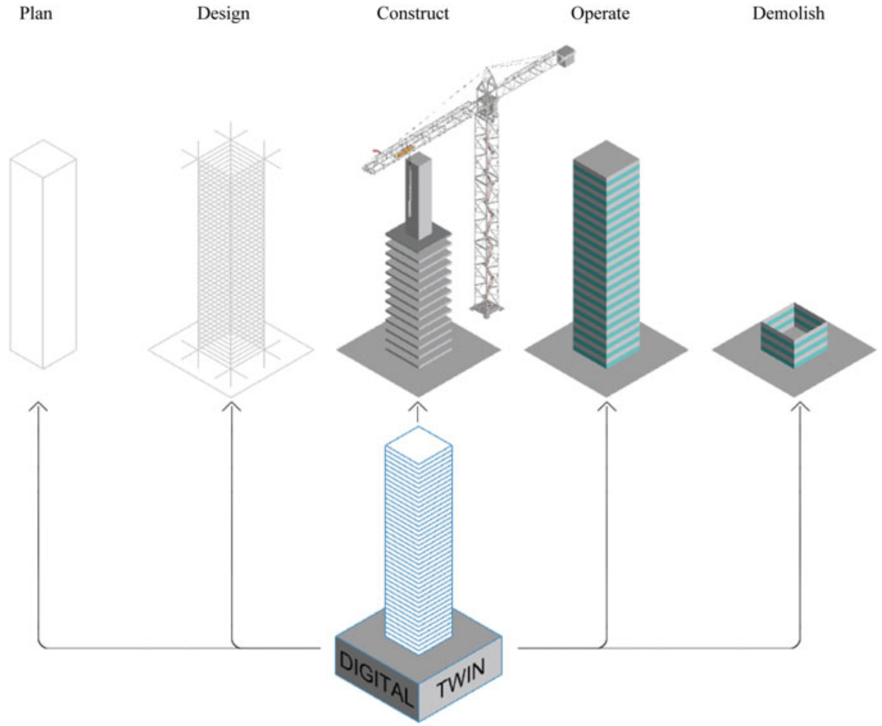

Fig. 6 Digital twins help to manage buildings during their entire lifecycle

a low-carbon economy. Digital twins can provide a simulation and monitoring tool, enabling the testing of policy decisions, identifying dependencies and enabling cooperation between policy sectors, all while improving the participation of citizens and communities.

7 Current Challenges in the Implementation of Digital Twins

To comprehend the present challenges in the adoption of digital twins in the Real Estate and Architecture, Engineering, and Construction (AEC) industries, it is necessary to examine the many types of user profiles that may be identified.

Tenants are one of the first user profiles to be considered because some of the data collected by the sensors may put their privacy at risk, but on the other hand, this data could be used to improve their living experience. Landlords, on the other hand, might benefit from having well-organised data on the digital assets they own and manage. Investors are another type of user profile who might be interested in learning more about the performance and management of a particular asset.

Vendors, technologists and start-ups are also important actors to consider, as they might be interested in receiving information on certain assets to advertise their services or adapt their business models to market demands. Nevertheless, it is vital to consider how local councils and governmental organizations might benefit from direct access to current information about assets and operations, enabling them to be more visible on the ground and providing citizens with better services. Research organizations and academic institutions are other interesting user profiles. They could use digital twins as virtual labs to collect field data for research and experimentation as well as to give students the chance to gain experience working with information that is typically challenging to obtain. Furthermore, government authorities, suppliers, insurance companies and similar businesses can benefit from having real-time data on the buildings for which they provide services [11].

Another important challenge to drive the adoption of this technology is the definition of standards. Standards are essential to establish definitions, concepts and processes such as data management and interchange, as well as technical requirements such as interoperability and data security.

In this sense several institutions are currently working to develop standards and frameworks to facilitate the implementation of Digital Twin technologies, an example is the National Digital Twin programme (NDTp) run by the Centre for Digital Built Britain, a partnership between the University of Cambridge and the Department for Business, Energy and Industrial Strategy [13]. Other examples are standards developed by the International Organization for Standardization (ISO) specific for the Digital Twin technology, such as ISO/IEC AWI 30173 “Digital Twin—Concepts And Terminology”, ISO/IEC WD 30172 “Digital Twin—Use Cases” and ISO/TR 24464:2020 “Automation systems and integration—Industrial data—Visualization elements of digital twins”. Also, important to consider are standards like ISO 10303 “Industrial automation systems and integration—Product data representation and exchange” and ISO 19650 “Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—Information management using building information modelling” [11].

Despite the increased use of digital twins in other industries over the past few years, which has made them more accessible, these technologies need a great deal of knowledge, and digital twins are challenging to implement in AEC processes, especially for small and medium-sized companies. Given the current state of technology, it is necessary to form multidisciplinary teams comprised of experts in fields such as software development, building information modelling (BIM), virtual reality, user interface design, interaction design, artificial intelligence and data science to connect IoT systems and create a system capable of streaming real-time data and allow users to interact with the system. Consequently, this technology requires considerable investment and requires the collaboration of multidisciplinary teams with different types of expertise. Therefore, it is important to consider the development of competency and skills frameworks to identify relevant roles within industry and organisations, as well as the key competencies needed to effectively implement these technologies. As a result, knowledge providers in this area can become important key players, because, without an adequate skill set, organisations risk employing staff with insufficient skills to develop their digital twin projects, with the risk of poorly designed results that do not work as intended [14].

8 Defining Building Ontologies

Real estate is one of the world's largest asset classes. Digital twins have the potential to significantly increase the value of real estate assets, from individual units to buildings and entire cities and facilitate the digitization of information relative to the physical assets. To achieve this and facilitate the implementation of digital twins it is necessary to define and set standards for digital twins [15].

The digital twin market is attracting tech giants like Microsoft, IBM, Siemens, Dassault Systems, Autodesk and others. These firms supply the digital infrastructure for IoT standards and protocols for data collection and analysis, enabling third-party companies to develop digital twins using the technology needed. The construction industry has been slower than other industries to embrace digital transformation. These companies are developing standards and integrations to support the acceleration of digital transformation in real estate. The software infrastructure that some of these companies are developing is important for the wider adoption of digital twins in the real estate sector (Fig. 7).

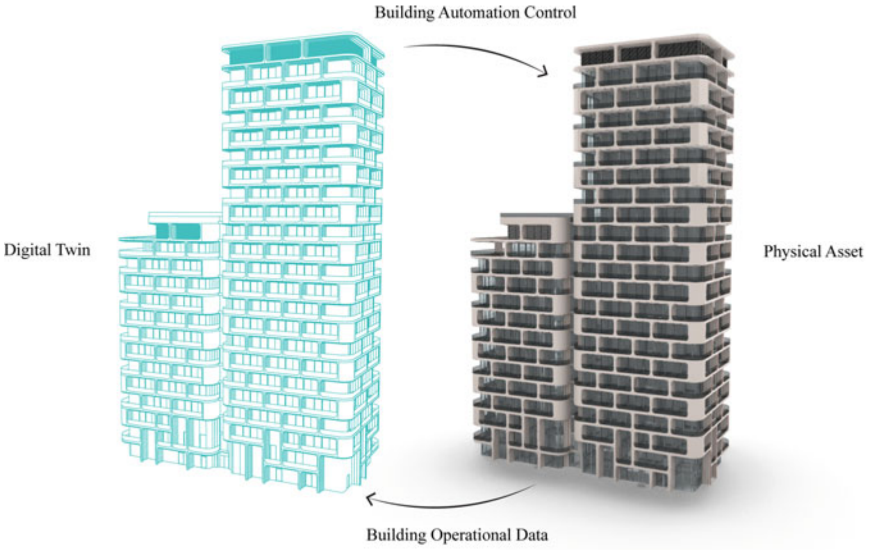

Fig. 7 The digital twin of a building allows for the digitisation of information about the physical asset through real-time data exchange

For example, if we consider a building element like a door, which is a common and essential item to have in a building, it involves several stakeholders to be specified, to be built and to be installed. Just to describe the characteristic of a basic item like a door it is required a considerable data structure, that nowadays is generally managed in BIM environment and requires specialized professionals and organizations to handle these building information models. To digitise real estate assets beyond the design and construction phases, it is important to simplify the way buildings can be described. This is why some of the tech giants interested in the digital twin market are developing new building ontologies that can be used to facilitate the implementation of digital twins.

An ontology in computer science is a formal representation of the concepts and interactions inside a certain domain. It is utilized to model and arrange the domain's knowledge in a machine-comprehensible format. Ontologies are frequently used in artificial intelligence, natural language processing, and the Semantic Web because they provide a standardized vocabulary for the comprehension and interpretation of data. An ontology consists of a collection of concepts, their attributes, and the links between them. It is used to describe knowledge so that it may be shared and reused across several systems and applications. In practical terms, a building ontology serves to conceptualize the type of data that are necessary to describe a building in all its constituent parts, describing the building elements, their properties and the relations between them. An ontology can be seen as a set of models for a specific domain. These models are developed through the use of a Digital Twins Definition Language (DTDL). A Digital Twin Definition Language (DTDL) is a standardized language or set of rules that can be used to describe the structure and behaviour of a digital twin. It enables developers to create a digital twin by defining the various components, their relationships, and the rules that govern their interactions [16]. For example, a digital twin definition language allows to define the various rooms in the building as components, specify the relationships between them (e.g., one room is adjacent to another), and define the rules that govern their behaviour (e.g., temperature control). The built environment is characterized by a high level of complexity, and a building ontology needs to express this reality in a manner that is simple for digital twin developers to use in order for this technology to achieve wide adoption.

By optimizing data categorization, integration, and accuracy, creators of digital twins may produce more accurate digital representations of buildings and their components. Therefore, the development of platforms that link data generated by IoT devices to the building topology is a necessary first step in setting standards for digital twins and facilitating the wider adoption of digital twins in the real estate sector [15].

9 Game Engines

Visual representation is an essential element that enables digital twins, allowing the user to understand the link between data and physical assets and to interact with them.

Game engines are playing an important role in facilitating the implementation of digital twins. Game engines offer technologies for handling the 3D data required to create a realistic representation of a physical asset. Most innovative manufacturers have started using game engines to simulate production processes and test their products with different usage scenarios before manufacturing them [17].

Game engines, such as Unity or Unreal Engine, include sophisticated 2D or 3D physics-based development environments that allow the development of photorealistic simulation while also providing an environment defined by physical forces and effects that can depict how the asset will interact with the real environment. This technology is important for the implementation of Digital Twins because, in addition to real-time data, the model may be simulated against physical circumstances that the user can adjust in real time. Game engines are used by innovative car manufacturers to simulate the creation of new cars and provide more immersive experiences by allowing users to try out a vehicle before it is built. Considering this example, digital twins are important for a wide range of people, including CEOs, marketing, sales teams and customers. Thanks to the visualisation and simulation capabilities provided by game engines, digital twins become more accessible: individuals no longer need a significant level of technical knowledge to understand or decode the simulation in front of them.

For example, non-technical people may experience how a new building will appear and work in a real-world scenario thanks to the strong visualisation capabilities of game engines [17].

10 Implementing a Digital Twin of a Building

The technology stack required to implement a digital twin of a building would depend on the specific requirements and goals of the project, but generally, it will include some essential components.

One of these components is the 3D modelling software, which is used to develop a virtual clone of the physical asset, including its geometry, spatial relationships, and materials.

The Internet of Things (IoT) system, which consists of sensors and devices, is another important element. It is used to gather information from the actual building, such as temperature, humidity, occupancy, and energy use. These sensors then feed the digital twin with the data they have acquired.

Another crucial element is the cloud infrastructure, which is utilized to store and handle the data gathered from IoT sensors and devices as well as any other data that is important to the digital twin.

Tools for analytics and data visualization are additional components required for creating a digital twin. These are used to analyse the data gathered from IoT sensors and devices and to present the findings in a form that is clear and useful to all stakeholders.

Other important elements are machine learning algorithms, which are used to identify patterns and trends in the data collected from the IoT sensors and devices and to make predictions about future behaviour or performance.

Application programming interfaces (APIs) are also important elements of a digital twin, these are used to connect the various components of the technology stack, and to enable integration with other systems or applications that may be relevant to the digital twin.

The user interface is another crucial element of a digital twin. This is the interface that stakeholders use to engage with the digital twin, and it may consist of web applications, mobile applications, or other types of user interfaces.

Developing the digital twin of a building requires a software architecture that can handle the various data sources, processing requirements, and user requirements involved in such a project. We can summarize the basic software architecture necessary for a digital twin in three main elements: the data management layer, the processing layer, and the user interface layer.

The data management layer is responsible for gathering and organizing the diverse data sources that will be utilized to create the digital twin. This data can include information about the building's physical characteristics, such as its 3D geometry and construction materials, as well as data on its systems and operations, such as energy usage and occupancy patterns. The information collected will be interpreted based on a building ontology specific to the type of building that thanks to the digital twin definition language (DTDL) will define the data model for the digital twin, which serves as a blueprint for how the data should be structured and organized. Once the data model has been defined using the digital twin definition language (DTDL), the data management layer can use this model to integrate data from a variety of sources and ensure that the data is organized and stored in a consistent and meaningful way [16]. This data can be collected by the data management layer from a variety of sources, including sensors, building management systems, and manual inputs. The data management layer should be able to obtain building-specific data updates in real time.

Another important component of the software architecture is the processing layer, which is responsible for analysing and interpreting the data collected by the data management layer. This can include tasks such as identifying trends and patterns in the data, predicting future behaviours and identifying potential issues or inefficiencies. The processing layer is not directly concerned with the structure or organization of the data but rather focuses on the meaning and significance of the data. The output generated by the processing layer can be used by users or other systems to make decisions or take actions. The processing layer should be able to handle large volumes of data in real time and should be able to scale up or down as needed to meet the needs of the digital twin.

Moreover, the software architecture should include a user interface layer, which allows users to interact with the digital twin and access the data and insights generated by the processing layer. This can include features such as dashboards, alerts, and visualization tools that help users understand and monitor the building's performance. The user interface should be intuitive and easy to use and should be accessible from a variety of devices, including desktop computers, tablets, and smartphones.

Overall, the software architecture for a digital twin of a building should be able to accommodate the project's complex and diversified data sources, processing requirements, and user expectations. The system of a digital twin must be designed with a scalable and reliable architecture to accommodate additional traffic and data volume.

11 Reference Projects

Having discussed the potential applications of digital twins and explored some of the challenges in implementing this technology, it is useful to discuss a couple of projects that provide a good example of how digital twins can be applied on the architectural and urban scale.

11.1 MX3D Bridge

The MX3D bridge, developed by the Joris Laarman Lab, is an innovative 12-m-long bridge 3D printed in stainless steel by the Dutch 3D printing company MX3D. The bridge is equipped with an innovative sensor system that will collect data about the bridge's structural behaviour and the environment. The data collected from the bridge is fed into a digital twin of the bridge, a virtual clone of the physical asset that analyses the condition of the bridge in real time, acquiring important information to understand how this innovative 3D-printed structure behaves from a structural point of view but also to understand how it interacts with its surroundings [18]. Funded by the Lloyd's Register Foundation, the project was developed in collaboration with several companies, including Arup, Imperial College London, Autodesk, University of Twente, Force Technology and the Alan Turing Institute. The sensors positioned on the bridge will measure real-time data like strain, displacement, vibration, and environmental elements like air quality and temperature acquired from the bridge while it is in use [19] (Fig. 8).

This data is used by research teams in the data-centric engineering program at the Alan Turing Institute to analyse material behaviour in diverse contexts and develop novel statistical methods to deepen understanding of advanced materials. The real

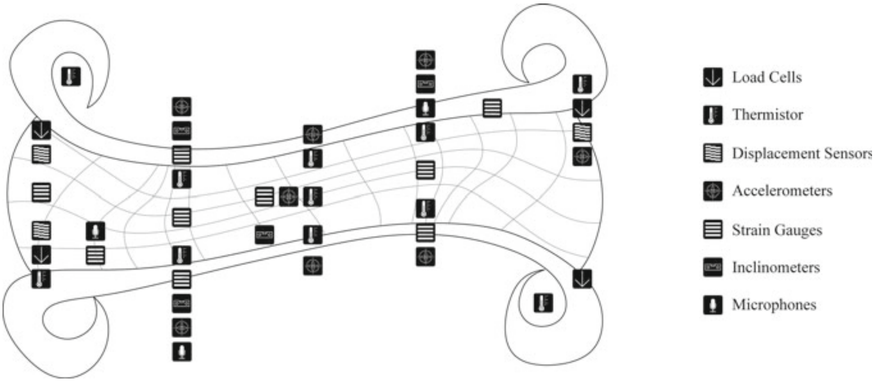

Fig. 8 Diagram representing IoT sensors embedded in and around the MX3D Bridge. (MX3D 2021)

bridge's performance is compared to that of its digital counterpart to provide relevant data for the design of future 3D printed structures and any upcoming certification requirements for 3D printed structures.

The University of Twente is collaborating on this project with its BRIDE program, which uses the bridge's data to study how people interact with it, provide feedback on the design, and assess the project's impact on the community by examining the interactions between people, place, activities, and technology [19].

11.2 Wellington Digital Twin by Buildmedia

Another interesting case study that implements digital twins at the urban level is the Wellington Digital Twin in New Zealand developed by Buildmedia in collaboration with the Wellington City Council. The project offers a new place for interaction powered by real-time city data. This digital twin makes use of smart city technology and real-time data to provide transportation statistics for buses, trains, ferries, bicycles, and vehicles, as well as visualisations of air traffic, cycle sensor data, traffic load, and available parking spaces. Considering that human beings typically process information through visual means, this model integrates data visualisation with a simulated real-world metropolitan context to achieve a strong visual appeal. To create an urban-scale Digital Twin with this level of complexity, it was necessary to combine data from different agencies [20] (Fig. 9).

The project started with the building of the 3D landscape using heightmaps derived from geographical data made available by Land Information New Zealand. More than 18,000 structures with 3D models and textures were built using a photogrammetry model of the Wellington Central Business District provided by the Wellington City Council. In this project, it is possible to understand the importance of adopting

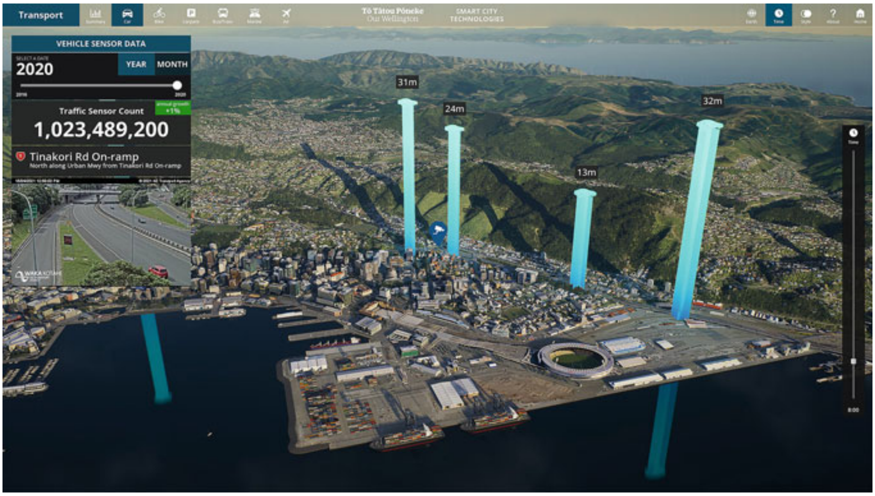

Fig. 9 Image of the Wellington Digital Twin developed by Buildmedia (Reproduced from Buildmedia 2021)

appropriate visualization technologies to construct Digital Twins, where the adoption of game engines allows the management of large quantities of data. The model was detailed using a variety of animation and 3D components, and the entire scene was handled within a physics engine capable of producing the atmosphere system that gives the scene a feeling of realism and enables the simulation of various environmental conditions. Then, this realistic replica of a real city was connected to a network of IoT sensors spread around the city. These data on traffic, pollution, and temperature are communicated using a custom REST API that can manage a variety of data formats, including JSON, XML, and HTTP [20].

Although the Wellington Digital Twin will continue to evolve, it is already being used to show a range of citywide initiatives for public consultations and meetings with stakeholders. Having all the information in one model simplifies and enhances interactions with local businesses and public stakeholders. The capacity to trace decision-making is also crucial; it is possible to start collecting a history of proposals and choices that will affect the city, enabling more participation and transparency with local inhabitants.

12 Potential Impact of Digital Twins in the Real Estate and AEC Industry

The impact that digital twins will have over the years in the Real Estate and Architecture, Engineering and Construction (AEC) Industry depends on several factors and it is difficult the predict since the technology will evolve and adapt over the years.

On the other side, it is possible to identify some specific areas in which Digital Twin could have a considerable impact.

One of the first aspects to consider is the impact that this technology may have on our society especially if digital twins are deployed on an urban or even national scale, which could lead to new ways of interacting with the built environment. For example, one of the goals of the National Digital Twin programme in the United Kingdom is to create a network of digital twins connected through shared data [21]. The establishment of such a building ecosystem might enable new services for citizens and could open new market opportunities related to real estate assets. Thanks to this technology in the near future buildings and structures could be augmented beyond their physical nature, becoming accessible online and providing new ways of experiencing them in the digital realm. This could also affect the value of physical buildings, introducing new digital economies linked to physical buildings.

The influence of digital twins on building sustainability and life cycle management is another essential scenario to consider. Thanks to their monitoring capabilities, digital twins can help reduce energy consumption and carbon dioxide emissions related to building assets. On the other hand, thanks to the data collected by digital twins during the life cycle of a building, they can become very useful to inform and activate recycling strategies at the end of a building's life cycle, promoting a circular economy and sustainable use of resources. Even small improvements gained via data-driven decision-making that can be enabled by digital twins might have substantial social, environmental, and economic consequences in a sector like real estate which represents a considerable percentage of the total carbon footprint of an entire country and a considerable portion of a country's gross domestic product (GDP).

Another field where we can expect digital twins to have a considerable impact is the field of software used to design and manage the construction processes. As the industry has evolved from CAD to BIM, we can expect to see new software becoming necessary to implement and manage digital twins in professional practice. Understanding the difference between BIM and digital twins is important to understand what the impact of digital twins could be in this field. The fundamental distinction between a BIM model and a digital twin is that the latter exchanges data in real time with the physical asset. A digital twin is an interactive platform that collects and visualises data, a living model that visualises information in real time and can be used to simulate user scenarios and environmental conditions based on the acquired data. While a BIM model transfers information primarily in one direction based on user input and the amount of information remains constant over time if users do not add new information to the model, a digital twin is a two-way information model that aims to generate feedback loops between the physical and virtual worlds to optimise the system performance. The accuracy of the digital twin should increase over time based on feedback loops between digital and physical assets. Due to the difference in purpose, a digital twin focuses more on dynamic data, whereas a BIM model focuses more on static data. This is not due to a technological constraint, in fact it would be possible to build a digital twin from a detailed BIM model. A digital twin during its life cycle should be able to provide more information than initially entered by the user. Digital twins should provide information on an asset's performance, as well as relevant feedback for improving the asset's design depending on the data collected. As more data is collected and comparable assets are deployed with their own digital twins, the accuracy of the representation of the digital twin improves.

Finally, it is important to consider how public and private organizations may develop or acquire the wide range of skills that digital twins necessitate in order to create a successful digital twin ecosystem. The skills required to build a digital twin range from data science to IoT, AI, BIM, and data visualization. This may require interdisciplinary partnerships, but also highlights the need for competence frameworks to assist governmental and commercial institutions in exploiting the full potential of digital twins. As a result, another potential effect of digital twins is that they can necessitate the establishment of new specialities and skill sets tailored to digital twin projects.

In conclusion, the application of digital twins is not yet widespread enough to disrupt the real estate industry, but as full digital twins of buildings become more common and standardised, companies will be able to optimise entire buildings, asset portfolios and lifecycles through a constant flow of data and information.

New business models and market opportunities will then emerge, as well as a change in the way places are conceived and created. Buildings could become more dynamic and responsive to human behaviour and the natural environment. In the future, it may be necessary to design not just the physical space of a building, but also its cyberspace.

References

1. Grieves, M., Vickers, J.: Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems. In: Kahlen, F.-J., et al. (eds.) Transdisciplinary Perspectives on Complex Systems, pp. 85–113. ©Springer International Publishing, Switzerland (2017)
2. What is a digital twin?. IBM. https://www.ibm.com/topics/what-is-a-digital-twin. Last accessed 15 Dec 2022
3. Apollo 13: the first digital twin. Simcenter. https://blogs.sw.siemens.com/simcenter/apollo-13-the-first-digital-twin/ (2020). Last accessed 15 Dec 2022
4. Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., Wang, L.: Draft modeling, simulation, information technology & processing roadmap. Technology Area 11, NASA, Washington (2010)
5. The technology. In: 37th America's Cup. https://www.americascup.com/the-technology. Last accessed 12 Dec 2022
6. Farrell, P.: Flying high at the America's Cup. Siemens Eng. Innov. (7), 46–53 (2021)
7. Huang, J.: NVIDIA to build Earth-2 supercomputer to see our future. NVIDIA Blog. https://blogs.nvidia.com/blog/2021/11/12/earth-2-supercomputer (2021). Last accessed 05 Dec 2022
8. Destination earth. In: Shaping Europe's Digital Future. https://digital-strategy.ec.europa.eu/en/policies/destination-earth. Last accessed 02 Dec 2022
9. Oligschlager, P., Strang, M., Winter, T., Bergsma, L., Van der Koelen, O.: Real Estate Innovations Overview, 6th edn. KPMG Real Estate Advisory (2021)
10. Hamilton, I., Kennard, H., Rapf, O., Kockat, J., Zuhaib, S., Toth, Z., Barrett, M., Milne, C.: 2022 Global Status Report for Buildings and Construction. United Nations Environment Programme, Nairobi (2022)

11. Hackney, W., Williams, K., et al. (eds.): Digital Twins For All. The Australia | New Zealand Digital Twin Blueprint, Smart Cities Council, Wellington (2021)
12. One third of the world's remaining safe carbon budget could be determined by urban policy decisions in the next five years. C40 Cities. https://www.c40.org/news/one-third-of-the-world-s-remaining-safe-carbon-budget-could-be-determined-by-urban-policy-decisions-in-the-next-five-years/ (2015). Last accessed 15 Dec 2022
13. National Digital Twin Programme. https://www.cdbb.cam.ac.uk/what-we-did/national-digital-twin-programme. Last accessed 10 Dec 2022
14. Plummer, D., Kearney, S., Monagle, A., Collins, H., Perry, V., et al.: Skills and Competency Framework—Supporting the Development and Adoption of the Information Management Framework (IMF) and the National Digital Twin. Centre for Digital Built Britain and Digital Framework Task Group, United Kingdom (2021)
15. Lawton, G.: Microsoft paves digital twins' on-ramp for construction, real estate. VentureBeat. https://venturebeat.com/business/microsoft-paves-digital-twins-on-ramp-for-construction-real-estate (2021). Last accessed 12 Dec 2022
16. Baanders: What is an ontology?. Azure Digital Twins | Microsoft Learn. https://learn.microsoft.com/en-us/azure/digital-twins/concepts-ontologies (2022). Last accessed 10 Dec 2022
17. Hart, B.: How game engines are revolutionizing digital twins. https://industrytoday.com/how-game-engines-are-revolutionizing-digital-twins/ (2021). Last accessed 30 Apr 2022
18. MX3D Bridge. MX3D. https://mx3d.com/industries/infrastructure/mx3d-bridge/ (2021). Last accessed 10 Dec 2022
19. Digital twin of the world's first 3D printed stainless steel bridge. The Alan Turing Institute. https://www.turing.ac.uk/research/research-projects/digital-twin-worlds-first-3d-printed-stainless-steel-bridge (2017). Last accessed 30 Apr 2022
20. Wellington Digital Twin. Buildmedia. https://buildmedia.com/work/wellington-digital-twin. Last accessed 02 Dec 2022
21. Bolton, A., Enzer, M., Schooling, J., et al.: The Gemini Principles: Guiding Values for the National Digital Twin and Information Management Framework. Centre for Digital Built Britain and Digital Framework Task Group, United Kingdom (2018)