Digital twins: A brief overview of applications, challenges and enabling technologies in the last decade [version 1; peer review: awaiting peer review]

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Abstract
The concept of Digital Twins (DTs) is an evolving idea, which is becoming the center of attention for the industry and the scientific community. It can be described as the pairing of the digital and the physical, interconnected for data sharing. DT is a key enabler for Industry 4.0, especially on the digitalization and visualization processes. Even though the idea of DT has been defined thoroughly throughout the recent years, there are still many different interpretations which are the result of different viewpoints of the involved professionals. The digitalization process requires huge amounts of data, which is generated, collected, handled and processed by various sources as well as digital twins themselves, thus offering new challenges that need to be addressed. In this paper, we attempt to i) assess the current state of digital twins, ii) describe the terms digital model and digital shadow as they are often misused as synonyms and iii) review the concepts of Internet of Things (IoT) and Industry 4.0 and discuss how these are connected. Moreover, some applications of DTs and their enabling technologies will be presented.

Keywords
Digital model, digital shadows, digital twins, applications, Industry 4.0, smart cities, Internet of Things (IoT)
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1. Introduction

In 2002, Michael Grieves introduced the concept of Digital Twins (DTs). According to Kritzinger et al., “DT in its original form is described as a digital informational structure about a physical system, created as an entity on its own and linked with the corresponding physical system”. The key point that should be underlined in the above definition is that DT models should ensure a pairing between the physical and the virtual system or entity and vice versa. To this end, all data that may be acquired from the physical entity may be retrieved from its digital copy (digital object). Therefore, DTs represent a dynamic equilibrium of information flow between digital and physical objects, as well as all the procedures, actuations and visualization of their entire life cycle.

The Internet of things (IoT) defines physical objects which are connected with sensors, actuators, processing hardware, and other related technologies that link devices and other sensors on the internet or other networks. Friedemann and Mattern define the IoT, as “the items connected to the virtual world where they are controlled remotely and can act as physical access points to the Internet services”. In addition, the IoT technology that gathers multi-source data is the major component of digital twins.

The massive changes in technology in the last century caused a great step forward resulting in a new industry revolution called fourth industrial revolution that transforms rapidly information management and the way that data is manipulated. Industry 4.0 is expected to increase the level of digitalization, automation, augmentation and decentralization in several domains and fields. To do so, a number of different technologies are leveraged, most notably IoT, Artificial Intelligence (AI) and Big Data Analytics.

To achieve the highest possible degree of digitalization, a lot of data has to be collected, thus making room for different kind of analysis in order to improve existing systems. To achieve higher level of efficiency, one has not only to collect data, but also visualize them in different ways allowing decision making that was not possible before. Since Industry 4.0 will provide the highest degree of digitalization and data visualization is needed, one can deduce that the digital twin model is one of the key technologies within the latest industry revolution. Using DTs together with AI, institutions may accomplish efficient management and optimization, create advanced products and services and expand the life circle of assets and business models. IoT connected devices are expected to be more than 75 billion by the year 2025. Based on the widespread application of IoT technology, since IoT is a core part of DTs it is anticipated that the research activity and applications in DT will spread accordingly. An analysis of the “IEEE Xplore” and “ScienceDirect” databases containing the term “digital twin” in the title confirms the above assumption and identifies rapid growing of scientific interest in the digital twin models in various disciplinary fields. Specifically, DT related engineering research have skyrocketed from 2017. The year 2017 seems to be a milestone year in the related research, since only in one year period (2017-2018) DT engineering research was tripled. Conducting a similar search in “IEEE Xplore” and “ScienceDirect” databases containing the term “digital twin” in the title for the period 2019-2021, it is evident that DT is still a rising scientific field.

The remainder of the paper starts with listing a few alternative definitions clarifying the terms of digital model, digital shadow and digital twin in section 2, as there are often used synonymously. Section 3 discusses different application of DTs in architecture, engineering and manufacturing along with their benefits. Section 4 discusses the challenges of digital twins. Section 5 lists the enabling technologies used in their development and section 6 concludes the paper.

2. Digital twin

As mentioned in the introduction section, the first formal definition about DT was given by Michael Grieves, establishing...
a basis for further DT development\textsuperscript{14}. In this section follows a list of different definitions that are set out through time.

**General digital twin definitions**

Based on Grieves' definition the National Aeronautical Space Administration (NASA) published a paper in 2012\textsuperscript{17} establishing further the definition of DTs. Specifically, digital twin was defined as following: “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”\textsuperscript{17}.

In 2017, Grieves and Vickers\textsuperscript{1} revisited the definition of the DT and added the terms Digital Twin Prototype (DTP), Digital Twin Instance (DTI) and Digital Twin Environment (DTE) to better distinguish the different manifestations of digital twin. Both DTP and DTI are types of a digital twin, built for different purposes. Specifically, digital twin is redefined as a set of virtual data structures that fully resembles a possible or real physical object in all levels of manufacturing process that range from micro to macro geometrical levels\textsuperscript{1}. Therefore, all data can be gathered either from the physical object or the respective digital clone. Grieves and Vickers defined the Digital Twin Prototype (DTP) as a type of digital twin that describes the prototypical physical artifact. DTP contains the appropriate information to define and create a physical version of an asset that clones the virtual one. On the other hand, (DTI) was set as a kind of DT that defines the physical object, which is associated with a digital twin throughout its whole lifecycle.

Later in 2017, Chen\textsuperscript{18} defined the DT as “…a computerized model of a physical device or system that represents all functional features and links with the working elements”.

According to Liu, Meyendorf and Mrad\textsuperscript{19} in 2018, “The digital twin is actually a living model of the physical asset or system, which continually adapts to operational changes based on the collected online data/information and can forecast the future of the corresponding physical counterpart.”

Similarly, Vrabic et al.,\textsuperscript{20} described the DT as “…a digital representation of a physical item or assembly using integrated simulations and service data. The digital representation holds information from multiple sources across the product life cycle. This information is continuously updated and is visualized in a variety of ways to predict current and future conditions, in both design and operational environments, to enhance decision making”.

One year later Madni\textsuperscript{21} defined DT as follows: “A Digital Twin is a virtual instance of a physical system (twin) that is continuously updated with the latter’s performance, maintenance and health status data throughout the physical system’s life cycle”.

### 2.2 Providing a more specific definition

While it seems like all different definitions agree that digital twins is a general computing model used for prediction and simulations of different scenarios, a more definitive definition is required. This problem is derived from the different user’s point of view and requirements from a suggested DT model\textsuperscript{22}. For example, users working on object/asset prototyping are using “first-principle dynamic models” as a copy of the physical object to be produced. Therefore, in this scenario, the term “model” refers to a set of mathematical formulas. In contrast, when the case is management and control, operators are mainly focusing on evaluating data implementing technologies such as machine learning and computational intelligence. Hence, this scenario implements the term “model” as an inference system that assess information and generates conclusions. Therefore, misinterpretations of DT are not uncommon between professionals from different backgrounds, since the focus point of the applications may be completely different.
Summing up from the definitions described above, someone may conclude that, in any case, a DT is a digital counterpart of a physical object. However, due to different levels of data integration between those two entities, a need of terms that distinguish these different entities arises. For instance, there are instances that data interpretation is modelled manually, while other instances have data fully integrated ensuring information flow between the physical and the digital systems in real time. Currently, academic and theoretical definitions of digital model, digital shadow and digital twin have been introduced to help us classify digital twins based on the degree of dynamic information flow in real time.

2.2.1 Digital Model (DM)
DM usually is a 3D representation of a real object or a prototype of an object under production that does not integrate any data flow between the real object and the digital (Figure 3). The DM may appear in various types of Level-of-Detail (LoD), meaning that users are able to document, articulate and specify the 3D model according to their requirements. Without any automatic data streaming taking place between the real model and the digital one, the digital model can describe several different aspects and models which make up the physical model, such as simulations models of industrial plants or models of new products. If data exchange exists, it is done manually, thus a modification in the state of either entity does not automatically reflect to its counterpart automatically.

2.2.2 Digital shadow
Based on the DT definition, when an automated data flow from the physical/real to the digital object occurs, then we witness the concept of the Digital Shadow (DS). Therefore, in DSs the state and condition of the physical object defines the current status of the digital object and triggers any changes accordingly, but not the other way around (Figure 4).

2.2.3 Digital twin
Going beyond the concept of Digital Shadows, if the flow of data among the real physical object and its digital counterpart is bilaterally interconnected as seen in Figure 5, then we can assume that we observe a digital twin. Therefore, the digital object may also trigger information and has impact on the physical one. This DT model may also be fully interconnected with other DTs (pairs of real and digital assets) that may stimulate changes of state between them.

3. Digital twin applications
This section focuses on the various applications of DTs in architecture, engineering, manufacturing and the rest of the industry. With the technological advances taking place in IoT and artificial intelligence, digital twins are also showing increasing interest.

3.1 Digital twins in smart cities
The cities of the world are growing rapidly in size and population, resulting in significant implications in our financial, ecological, industrial future that affect global communities. To address the shocking consequences, in terms of global resilience and sustainability concerns, many communities are applying high-tech advances in their structures for intelligent management, including into their strategies the smart growth agenda. The emergence of the concept of digital twins fueled by the technical abilities offered by IoT, is the basis for the establishment of digital twins for a Smart City. The digital twin city that is updated by the performance of the natural city infrastructure and human energies is gradually able to predict state changes in systems and forecast possible upcoming actions. The forecasting mechanism could be operational in real-time and could aggregate historical information of infrastructure systems installed throughout the physical city. In addition, a DT in smart city may study what-if scenarios in the system, estimate the result and propose the appropriate preventive actions. This could assist analysts clarify how smart cities are likely to achieve high degree of resilience and adaptability in changing

Figure 3. The flow of data in a digital twin.

Figure 4. Data flow in digital shadow.

Figure 5. Data flow in digital twin.
economic, environmental and social conditions, identifying potential outages or malfunctions along the way. The ability of services and infrastructure in a smart city to have sensors and be monitored with IoT devices is of great value for all kinds of future protection, such as the design and development of current smart cities, as well as assistance in the ongoing development of other smart cities.

Digital twins can also be used to optimize vehicle traffic. It is possible to transmit data in real time, such as location, speed and route from vehicles traveling in the digital duo. The digital duo can then reduce the travel time of vehicles by performing simulations of possible movements under different possible traffic signal designs. The digital twin system can utilize the accurate information of all road users to calculate the best routes that save travel time for each vehicle and also reduce overall fuel consumption. In addition, to increase effectiveness and traffic safety, scientists are studying and experimenting in the rapidly growing fields of Vehicle-to-Vehicle (V2V) communications and Vehicle-to-Infrastructure (V2I) technologies. For the past decade, the research has been focused on autonomous and interconnected vehicles for effective control, proper fleet management and traffic flows demonstrating high safety levels.

In addition, some Practical Smart Cities applications include integrated assessment modeling for monitoring air pollutants and greenhouse gases to maintain sulfur, nitrogen products in low levels and ensure ecosystem protection.

In addition to optimizing traffic and evaluating pollutants, another area of interest is energy forecasting. The electricity network system can be considered as a basic energy component for a modern energy system, connecting other forms such as solar energy, aeolian energy, fossil energy sources (e.g., natural gas), as well as alternative fuels. Such a prototype is demonstrated in Figure 6 and Figure 7, where the prototype DT system was designed and implemented on electricity system of the University of Denver (UoD). In Figure 6, the system shows the structural design of the electricity system and the prototype’s response on various control selections for different scenarios with renewable energy sources. Figure 7 shows the actual response of a selected control strategy, namely, social costs, renewable energy production, load and electricity price. As a result of a well-defined DT, real-time information may be assessed and analyzed in order not only to improve performance, but also to accurately and efficiently predict severe effects due to climate factors.

Ruohomaki et al. introduce “mySMARTLife”, a framework that uses IoT to create a DT. Using open data, the project contains real, extended data as well as calculated building data for integrated energy efficiency upgrades and energy efficiency classifications. In addition, the heating energy sources along with the estimated building energy consumption were calculated by the Technical Research Center of Finland VTT. The authors conclude that the connection of sensor data to a city model is the basis of a DT. The proposed platform forms an ecosystem for analytics companies in which they can develop their services.

Jo et al. proposed an idea to design a smart pig farm, using DT to improve animal welfare as a feasibility study. The authors suggest that due to the spread of DT, livestock farming has been reproduced and simulated to be more robust against livestock disturbances in the virtual world and to apply the results to livestock farms in the real world.

Sivalingam et al. demonstrated a new methodology for foreseeing the life cycle of a wind turbine in a wind farm, which is reflected into a digital twin model for strategic maintenance forecasting. Wind farms require high-reliability wind turbines to reduce maintenance costs and shorten interruptions in operation. By assessing the residual useful life of wind turbines for both analytical and prognostic monitoring, the proposed DT
framework succeeded in providing the optimal prognostic maintenance strategy.

3.2 Digital twins in manufacturing

Another established application for digital twins is the manufacturing industry, as manufacturers are always looking for methods to become more efficient and thus, save time and money. Grieves also introduced the concept of digital twins in 2002, to create a Product Lifecycle Management Center. As the production process becomes more complex and smarter, manufacturing products become more complex.

Since product design and production units are based on modularity, a DT model in manufacturing offers a solid base to emulate and optimize the production line, including the accompanied logistics aspects. At the very same time, it may provide a very helpful visualization of the process (usually in 3D) from individual parts of a manufactured equipment to its complete assembly. This means that an autonomous production system can be created with the ability to react to unforeseen events in an intelligent and efficient way. With the help of the IoT, the idea of DT may be incorporated at every step of the complete life cycle of a product, as illustrated in Figure 8.

As a result, DTs can assist professionals in production, programming and control. For instance, specific abilities such as automatic product planning and execution of orders from the production units may be inferred by a smart environment of intelligent order scheduling and decision support systems. In addition, DTs can also assist in the maintenance phase. They can determine the impact of status modifications of the production line and evaluate system states based on Artificial Intelligence and Machine Learning. In addition, they can integrate, and analyze and handle information flow through the distinctive phases of the machine life cycle to manage information more efficiently and acquire a complete visualization of a machine’s condition. Of course, DTs can also be used in device design as they can continuously evaluate a production system and automate independent data acquisition.

It is also worth noting that the construction of more complex systems means that there is a greater risk of errors. A slight failure during production can cause irreparable losses. Thus, error diagnosis is of paramount importance in intelligent construction. Using digital twins, the error diagnostic standard is transformed from a purely data analysis into an immersed experience.

Bambura demonstrated the feasibility of a digital twin application in the real state of a manufacturing plant specializing in the manufacture of aluminum components for the automotive industry. The conclusion of the paper was that the DT application seems to be a promising real-time optimization tool, as the authors managed to increase the productivity of the production line.

Another challenge facing manufacturing industries is the total use of energy in their production processes. To maximize profits, these industries should ideally reduce their energy footprint without adversely affecting their overall productivity. Understanding the use of energy in each individual stage of each process is vital in order to optimize costly processes and ultimately reduce energy consumption, which in turn will maximize profits along the way. According to 48 intelligent control of energy uses combined with energy efficiency technologies, can reduce energy consumption by 50% as opposed to improving operation, which can reduce it by up to 20%.

Jackson combined cloud-based data storage with sensor-equipped kits, a management portal in the sense of digital construction, and data analysis with Discrete Event Simulation (DES) to present a modular, modifiable framework called M4 – “Meggitt Modular Modifiable Industry.” A case study demonstrated the flow of information among entities in the DT model and revealed that M4 has great potential for creating configurable production systems, offering high routing flexibility.

Rodić and Kandu presented a complete simulation model of a factory using DES software, AnyLogic and a new heuristic algorithm, which produced an optimized machine layout on a store floor. Jain and Lechevalier presented a methodology for automatically generating multi-resolution virtual factory models using real factory data.

Terkaj, Tolio and Urgo built a virtual factory that guarantees digital continuity between the factory and the virtual model. To achieve this, the researchers used continuous ontology updating with real-time data combined with historical models. Utilizing virtual reality to help users visually, the tool could be used for management and programming.
Pelliccia et al.\textsuperscript{53} presented two methodologies for the energy visualization of various machine tool components in VR. In this study, the energy values were set experimentally by measurements acquired from the machine, but those methodologies were based on a fixed framework and are related to a unified configuration.

Niu, Pan and Zhao\textsuperscript{64} used VR technology to collect completeness information in the energy design of buildings. The goal was to identify the most energy efficient design plan based on the efficiency gap and energy requirements. Using Building Information Models (BIM) to model different models and applying this methodology to a case study, the authors were able to identify unexpected problems. The results showed that the designers were able to determine the best design plan for the behavior of the target passengers.

Hermann and Zein\textsuperscript{55} used AR to visualize the energy flow of production processes in order to identify problematic hotspots and make improvements. By installing sensors in machines, the authors were able to use electricity, refrigerants, temperature changes, compressed air, heat loss, raw materials and emissions as inputs. The application succeeded in identifying the highest rate of energy expenditure.

### 3.3 Digital twins in healthcare

The healthcare sector is another area for DTs. With the rapid expansion and developments in many activation technologies, this field offers enormous potential. Due to the fact that the prices of IoT devices become lower and simpler to implement, the actual network connectivity is magnified\textsuperscript{66}. Liu et al.\textsuperscript{37} proposed a new idea of Digital Twin Healthcare (DTH) in 2019. DTH was proposed as a novel medical simulation method to provide robust, precise and effective medical services using technology combined with multidisciplinary, multi-physics and multi-scale models. DTH can be used in the management and design of the hospital as well as in the health care of patients. Using DTH, various scenarios can be assessed in a virtual environment before scheduling and implementing actual changes, such as scheduling beds and staff schedules. Without DTH, hospital staff can rely only on the knowledge of the field and its basic analysis to plan its actions, however the use of a digital duo will reduce the risks and save costs.

Zheng et al.\textsuperscript{58} proposed an effective and highly confidential, query-like healthcare monitoring plan based on a digital twin platform. The aforementioned system consists of four types of entities, a health center, its patients, digital twins and a cloud server. Each patient has multiple sensors that collect their normal data in real time, which are then sent to the digital duo. In this case, each patient is connected to a digital twin and digital twins are smart programs that only monitor a patient’s state of health. The input is the data collected in combination and the output is the results of the diagnosis and the treatment proposal for the patient. The cloud server is used to provide digital twin healthcare tracking service.

Laaki et al.\textsuperscript{39} harnessing the power of the IoT created a new functional prototype of autonomous surgery to create a DT of a patient. Using a robotic arm and an HTC Vive VR headset, the researchers developed a prototype remote surgery application using a mobile network. The authors state that due to the complexity of the project, they used simulation instead of a physical model in the real world.

Ross et al.\textsuperscript{60} presented a paper by Hewlett-Packard using IoT that allows them to create digital models of people they call avatars. HP says it can position users’ avatars through workouts, exercise routines and diets combined with medical data to predict your health based on a number of different lifestyle choices. While the potential of this application is huge, HP sees a much more immediate application and market value in the apparel industry. In addition, HP is seeing further implementation of this system in games.

#### 3.4 DT in the industrial sector

In 2016, General Electric (GE) reported the application of DT technology through a patented application\textsuperscript{71}. GE has developed an industrial IoT platform called “Predix”\textsuperscript{64}, which can be used as technology to create digital twins. Predix was used to monitor and analyze data. Some Predix applications include programming and logistics, interconnected assets, smart environments, industrial analysis, asset and application performance management, as well as and function optimizations\textsuperscript{67}.

Embracing the idea of Industry 4.0, Siemens has developed a cloud-based platform called “MindSphere”\textsuperscript{76} that connects physical infrastructure and machines to a digital twin. MindSphere can provide digital twin solutions as it uses billions of data streams as well as all connected devices that hope to transform businesses and provide digital twin solutions\textsuperscript{69}.

Another platform for implementing DTs is “ThingWorx”\textsuperscript{62}. In 2014, PTC acquired ThingWorx and further extend it into a key Industrial IoT platform by incorporating PTC’s Internet-based Product Lifecycle Management program. The platform includes many components such as ThingWorx Studio, ThingWorx Analytics, ThingWorx Utilities and ThingWorx Industrial Connectivity. All these different elements of work are combined in the ThingWorx Foundation, which is the central part\textsuperscript{62}.

The ThingWorx Foundation supports connections to different connected components with end-to-end security technology, enabling operators and managers to link, build and develop industrial applications across the IoT platform, as shown in Figure 9. ThingWorx guarantees the production of detailed data, also providing a stage where DT solutions can be developed\textsuperscript{62}.

The Watson IoT Platform, developed by IBM, is another DT platform\textsuperscript{49} commercially available as a complete IoT data tool. The platform collects data from millions of IoT devices, enabling large-scale systems to be managed in real time. The
platform can be used to build a digital twin system as it offers cloud-based services, blockchain services and data analytics.

In addition to closed source solutions for digital twins, there is an open source project called “iModel.js”, which is provided by Bentley Systems\(^6\). This framework has powerful tools for gathering infrastructure data and offers tools for visualizing different types of data, such as BIM, GIS, IoT, 3D or 4D data streams using a standard web browser. In addition, it provides an accurate record of who-changed-what-when, which means that services and applications can obtain a copy of the digital duplicate and subscribe to change notifications. Upon notification, each digital duo receives changes and applies them to their local copy.

### 3.5 Digital twins in heritage

The digital twin technology can also be leveraged in prescriptive maintenance and damage prediction from various sources in heritage sites increasing the prospects of preserving and revitalizing them. Due to the fact that heritage sites and historical buildings have to be preserved in a way that they are everlasting in time, DT models can be used to simulate various phenomena or different environmental states, which will provide less wear over time.

Wang \(\text{et al.}\)\(^6\) explored how wind erosion affected the Yongling Mausoleum in China. To achieve this, a digital model of the studied area was initially created and with the combination of collected weather data as well as computational fluid dynamics (CFD), a prediction of wind erosion over each single individual building was made possible. After collecting hourly weather data over a two-year period, the average and maximum wind speeds were calculated. Then, by building a detailed geometrical model of the Yongling Mausoleum and feeding it into the CFD solver, together with the gathered weather data, the researchers were able to calculate wind pressure values at each individual building, which helped them estimate the erosion caused by the wind, without any in situ measures. As a result, they suggested a greening plan, which required planting trees and shrubs in rows as well as windbreak green turfs. After re-running the CFD solver with the newly updated mesh which included the greening plan the researchers were able to identify that the wind erosion on the historical building would be drastically lower. Figure 10 and Figure 11 compare the pressure before and after greening to better illustrate how the wind pressure dropped.

Another application of digital twin technology for heritage site preservation is referenced by Pineda and Iranzo\(^6\). They generated a Digital Model of the heritage site in Baelo Claudia in Spain that was used to analyze the sand-loaded air flow erosion using CFD. After gathering the required weather data to configure the properties of the CFD solver, a damage prediction for the next 50 and 100 years was made feasible. After the simulation took place, the researchers proposed that transparent erosion-resistant coverings can be placed to the affected areas to reduce destruction. Moreover, as a potential remedial measure, they suggested the installation of a wind baffle at a certain location. According to this suggestion, the wind baffle would deflect the sand-loaded air flow, thus preventing the sand particles from directly impacting the currently affected area. To support their suggestion, the authors re-executed the CFD simulation with the wind baffle in place, to visualize the damage to affected areas, which indeed was mitigated to a certain extent.

In contrast to the case studies at the Yongling Mausoleum and Baelo Claudio, another use of the digital twin is at the Slender Minaret Madrasah in Konya (Figure 12). Yasa \(\text{et al.}\)\(^6\) used CFD simulations in Ansys Gambit software to determine the comfort of indoor building users. Taking into account various factors, such as temperatures in the air and in the surface of the buildings, air fluctuation rate, relative humidity and illumination levels, they concluded that the Slender Minaret structure meets the criteria of thermal comfort (Figure 13). Moreover, they proposed that for historic buildings and those of traditional construction, the right balance for each monument must be found, between the effective preservation of the building and the appropriate measures to improve energy efficiency, if permanent damage to both the character and the importance of the building and its structural material is to be avoided.

Another case of use of digital twins together with the use of CFD is reported by D’Agostino \(\text{et al.}\)\(^6\). D’Agostino observed the Crypt of the Cathedral of Lecce in Italy for a period of one year and developed a digital model in which a simulation of thermo-hygrometric parameters and air flow patterns was applied to reproduce the crystallization of salts and the deterioration of works of art. Two conditions were reproduced, one being the current microclimate in the crypt, which presented inadequate storage conditions, and another microclimate resulting from proposed changes, which led to a more suitable situation. The researchers found a scenario that can prevent damage
Figure 10. Yongling Mausoleum wind pressure before greening (under the terms of the Creative Commons CC-BY).
Figure 11. Yongling Mausoleum wind pressure after greening\textsuperscript{66} (under the terms of the Creative Commons CC-BY).
and help preserving the current state of the crypt. Thanks to the DT and the CFD simulation, the authors proposed that windows should not all be open simultaneously since, this triggers risky microclimatic conditions. Additionally, they proposed a double glass installation to help the Crypt’s maintenance.

Jouan and Hallot\(^70\) suggest that a combination of Heritage Building Information Modeling (HBIM) and DTs allows the creation of preventive conservation mechanisms for cultural heritage sites. The authors propose a framework that integrates the use of DTs in the management plan process for proactive safeguarding of heritage sites (Figure 14). The researchers argue that the use of semantically enriched HBIM models with real-time IoT data provided by on-site sensors combined with DTs technology enhances the link between the physical field and the digital model. As a result, personalized information can be provided to non-specialist stakeholders engaged in the decision-making process for the administration of cultural heritage sites.

Eloisa et al.\(^71\) leveraged the HBIM model to create a digital twin of Pampulha Modern Ensemble (PME). The researchers created a detailed HBIM model for PME that contained the heritage elements in an organized fashion. Additionally, AR technology was used to retrieve various information from the HBIM model, thus allowing the development of an application which promotes the diffusion of historical content differently and innovative with the use of immersive environments. The developed app enhances visitors’ engagement with the heritage site since it is easy to use and provides a straightforward way

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**Figure 12.** (Above) Exterior and interior view of the Slender Minaret Madrasah in Konya, (Below) the monument modeling in Ansys Gambit software\(^68\) (under the terms of the Creative Commons CC-BY).
to obtain information regarding the history of the building, the biography of the architect and explore the components of the building in an interactive way.

Gabellone\cite{Gabellone} developed a digital twin model of an underground oil-mill in the town of Gallipoly, Italy. Afterwards, a web app was developed to allow virtual visits assisted by a real time remote guide. The realism of the 3D model of the oil-mill is guaranteed by using digital photogrammetry of more than 3000 images. Multiple users can connect using various platforms such as their web browser or VR headsets. In his case study, the author suggests that by developing a digital twin model can help users gain a better understanding of the real space. Additionally, the digital twin can assist in overcoming physical and cognitive barriers since the real space has access limitations for people with disabilities.

4. Challenges
It has become apparent that since digital twins run in parallel with several different technologies such as AI, IoT and data analytics they also share the same challenges to some extent.

4.1 IT infrastructure
In order to access and process huge amount of data, the IT infrastructure has to consist of up-to-date hardware and software. For example, due to the Covid-19 pandemic the cost for high end graphics processing units (GPUs) that usually run AI algorithms and simulations has skyrocketed\cite{GPUCostIncrease,GPUCostIncrease2}. To overcome this challenge, many companies are using on-demand GPUs through cloud services like Amazon, Google and Microsoft. Furthermore, the use of the cloud for data analytics and DTs may create critical security issues. Hence, without a well-designed and scalable IT infrastructure, the DT model may not succeed to fulfil its purpose.

4.2 Data
All data needs to be sorted and presented in an appropriate manner in order to be fed into the required algorithms and tools\cite{DataManagement}. Therefore, a constant, noise-free stream with high quality data is required. Inconsistency in data presents a performance risk in the digital twin, as it will act on corrupted or missing data\cite{DataConsistency}. Therefore, the quality and quantity of IoT data is an important factor for the collected information, which

Figure 13. Wind velocity diagrams in the digital model of the monument for the two selected dates of the experiment\cite{WindDiagrams} (under the terms of the Creative Commons CC-BY).
present the need of careful planning and analysis beforehand in order to implement efficient digital twins.

4.3 Privacy and security
No matter the use case, privacy and security are important topics for everyone involved in the industry. Especially within the digital twins setting, because of the vast amount of data as well as their sensitive nature achieving privacy and security is a big task at hand. We can safely conclude that following the best practices for security and privacy for every technology involved in the digital twin, such as IoT, AI and data analytics is of utmost importance. Besides the best practices for every technology, digital twins should also comply with the General Data Protection Regulation (GDPR), which ensures the privacy and security of personal data in Europe. Additionally, federated learning, which provides the ability to train large-scale models in a decentralized manner, avoiding direct access to user data, has to be taken into consideration when

Figure 14. The digital twin process to include strategies for preventive conservation of heritage sites (under the terms of the Creative Commons CC-BY).
implementing data analytics within a DT. It is apparent that privacy and security challenges leads to another challenge, which is trust. DTs need to lay a foundation in order to ensure and prove to users that privacy and security concerns that users may have already been addressed.

4.4 User expectations
Even though digital twin technology has been accelerated by researchers and industry leaders such as Siemens and GE, user expectations is another challenge, since DT sounds like the technology that combined with AI, Deep Learning and IoT may solve many of our problems. User expectations should be set, discussed and evaluated continuously throughout the development process of DT systems.

4.5 Standardized modelling
Another challenge which exists in all types of DT implementation relates to system modelling since there is no industry standard on how exactly each model should be built. By definition, DTs can be built to solve totally different and unrelated problems, which belong to numerous scientific fields. Therefore, there is a need for a standard approach from the initial design phase to the simulation of DT. Standard approaches guarantee the data flow between the different stages of a DT while also ensuring user understanding.

5. Enabling technologies
Important enabling technologies for DTs are presented and discussed in the following paragraphs.

5.1 Internet of Things (IoT)
IoT describes a vast array of objects with detectors and actuators that accumulate, analyze, and distribute information with other entities, systems, and platforms. The term “Internet of Things” was introduced in 1999 by Kevin Ashton. According to him, computers with sensor technology are able to detect, identify and understand the world without the restrictions of human-entered data. Koohang et al. states that “In 2018 the number of IoT devices was estimated at over 17 billion, while it is estimated that by 2025 there will be more than 75 billion devices with the industry forecasting a value of over $5 trillion.” The large number of connected sensors supports the concept of a fully connected world. The use of IoT devices is globally beneficial, having a major impact not only on our daily lives, whether has to do with the healthcare system, transportation, communications but also in industry with emerging concepts such as smart cities and smart construction. Since DTs are by definition based on the automatic communication of data between their respective physical objects, IoT is a fundamental block in the process of creating DT applications.

5.2 Data Analytics (DA)
Data analytics is the science of integrating diverse data from various sources, inferring and predicting decisions, achieve a competitive business edge, and assist in strategic decision making. DA has developed under various kinds, such as electronic analytics, data mining, visual analytics, big data analytics and cognitive analytics. In addition, the term “analytics” is also used to describe data-based decision making. In addition, data analysis involves manipulating and calculating large volumes of data to identify patterns, correlations, and other useful information. Since IoT gather vast amounts of data, data analytics are another enabling technology for DTs in order to allow applications to draw conclusions and display relevant information to enable smart decision making by its users.

5.3 Artificial intelligence
Artificial Intelligence (AI), as well as its subcategories like machine learning and deep learning, are crucial in elevating the manipulation of data and information extraction to a higher level. By using AI and its subcategories, DTs are transforming from being just a digital object to a smart entity, which users can leverage to achieve their goals. Using AI, they can be assisted in making the right decision for a task at hand. Additionally, AI can sometimes solve problems more efficiently, using solutions that were not even considered in the first place. This reduces time that the users would otherwise waste in a problem, as well as costs, since optimal solutions are always preferred.

5.4 Data visualization
While data visualization is not a technology itself, it is of utmost importance in the implementation of a complete digital twin model. With the vast amount of data and information that DTs offer, relevant data has to be presented in a fashion that is understandable by users (e.g., graphical representations), thus allowing them to focus on what is important without distractions from an overwhelming amount of technical data.

6. Conclusions
Thanks to the technological advancements in recent years, digital twins are experiencing an unprecedented growth, judging from both the published scientific papers, as well as the large investments from the private sector. This would not be possible without advancements in technologies such as IoT, data analytics and AI, which are now the most important catalysts for DTs. While currently the majority of the applications of digital twins lie in the manufacturing field, we can already identify use cases in other fields, where these applications have proven to be beneficial. Currently, with the rise of Industry 4.0, we can already identify a shift with major companies, such as General Electric and Siemens who are trying to create digital twins in a huge scale, investing heavily in their development. For the time being, realizing and implementing effective digital twins is still a work in progress, since certain challenges such as standardization, IT infrastructure and privacy concerns have to be resolved to some extent. Additionally, in the smart cities sector, digital twins seem to be gaining more ground as the interest to develop smart systems will save time, prevent problems before they even present themselves and ultimately reduce costs along the way. Moreover, another promising use case of digital twins appears to be in the healthcare sector as in the future they may very well be used to save lives. However, the technology still has to overcome certain privacy challenges, due to the sensitive nature of the data. Furthermore, we discussed several cases in the cultural heritage field, where digital twins combined with the technology of CFD simulations, have provided details for prescriptive maintenance and have acted as preventive mechanisms for damage...
Data availability
No data are associated with this article.