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Options for and Challenges of Employing Digital Twins in Construction Management

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Abstract: The notions of smart construction and smart or digital cities include many modern concepts that are advocated today, especially in countries with advanced economies, and depend on using information technology and the Internet of Things as a basis to automate processes and activate digital systems to manage activities and services related to the operation of buildings and urban structures. In light of the spread of digital technology and modern managerial approaches, the concept of a digital twin is being used on a large scale with the current trend and direction to digitalize activities providing many economic, social and technical advantages. A digital twin is a system in which a virtual representation of a real entity or physical system is used continuously by being fed with data and deriving outputs in the form of decisions and actions that are generated through the processes of machine learning, simulation, development and lifecycle management. This study aims to review the literature on construction project management through the lens of digital twins and ways to use them in the field to improve operational results. The authors propose a framework for analyzing and supervising the development of digital twins that uses three main stages: the commonly encountered Building Information Modeling (BIM); the existing monitoring and actuation digital twins; and an envisioned third stage that makes use of artificial intelligence, complex visualization instruments and advanced controls with the capability to exact change within a construction project on the building site.

Keywords: digital twins; construction project management; cyber-physical system; construction management; smart building; engineering project management

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1. Introduction

The concept of a "digital twin" refers to a model that uses technical and managerial processes that combine real and virtual environments to manage and process data and to control physical systems. Digital twins have become widely used in the fields of manufacturing, production and operations management and have also been introduced into the fields of construction, infrastructure and civil engineering [1]. The idea of a digital twin is built around the role of a virtual copy of a target physical entity that is used to conduct experiments or simulations and predict future behaviors to help decision-makers make up their minds or to help automated decision systems determine appropriate solutions to the expected problems [2]. A digital twin can be used in construction project management processes by providing its database with information and data through sensors that monitor the execution of work and the behavior of the commissioned facility after construction. In this way, the database provides the ability to compare the ideal situation to reality and the possibility to track the work through specific monitoring cycles and produce necessary reports and alerts for managers [3].

In this study, the digital twin is discussed and analyzed within a structured framework, starting from the goal of being able to respond intelligently to expected events. The work presented here aims to link the results of exiting studies to obtain a clear vision of executive construction project management and support the development of a comprehensive digital system that employs digital twins to solve specific construction project issues, such as budget and timeframe overruns, worker safety and environmental impact. By obtaining an integrated digital support system for managing operations at construction sites that is based around a coherent vision, the authors expect to provide companies operating in the field with a deeper understanding of the gains they could experience by moving away from outdated management approaches.

This study assumes that the smart construction model simulates reality, can predict technical and economic risks and has the possibility of using digital twin functions in distinct phases, such as intelligent analysis in design (e.g., for structural engineering or utility management), on-site project implementation, the operation of buildings and facilities etc. This is due to the fact that using sensor data for processing, analysis and deploying the correct software solution depends on the lifecycle stage of the building, thus varies in scope, complexity and purpose.

The main contribution of the current research consists of defining an overarching model for digital twins for construction projects (DTCP) that integrates mature, emerging and future approaches within the field into maturity stages that a company can follow. The framework is based on an integrative outlook that pursues the organizational and project management benefits of using a diverse array of digital technologies depending on their adequacy for certain applications, ranging from reducing costs to tracking health and safety hazards.

2. Methodology

The study adopted the methodology of reviewing and analyzing the literature and linking existing studies to obtain an integrated framework for managing construction industry projects that could help to combine the simulation of the components of activities within the digital twin system with the actual building site. In this way, the framework could provide support for decision-makers in tasks related to operations within the successive implementation stages of a project.

The literature to be studied was selected using the following criteria/stages:

- Mostly articles and studies published in the past 5 years, 2017–2022, to ensure the generation of the correct picture of the latest developments; very few studies were selected from before 2017 and they were chosen mainly for their ability to describe the basics in detail, as is necessary in the industry that we targeted;
- The use of two databases and search systems to increase coverage; one was a subscription service (ScienceDirect by Elsevier) and one was open access (Google Scholar by Google);
- The keywords to be searched were those used at the beginning of our paper, but they always required a combination of the actant (digital twins; cyber-physical system; or smart building) and the acted upon (construction project management; construction management; engineering project management)";
- Additional papers within the same area of interest were also acquired from the bibliographies of the main studies/reviews that were employed for our analysis to make sure that a complete understanding of the findings was possible;
- A balanced coverage of various countries/continents was also observed in order to avoid geo-cultural biases, and some non-scientific articles and papers of high relevance were also included in the analysis;
- The 58 papers and articles found in this way underwent a redundancy check, an elimination process for articles beyond paywalls and a basic structuring into categories.

In the end, 40 works were selected and used throughout our analysis, depending on the combined content that they provided. Building upon this analysis, the authors then consulted experts in the fields of civil engineering, digitalization and project management to help to define a framework that could be useful to companies working in construction project management that are interested in making use of the benefits of digital approaches.

In total, six experts (two from each domain) were consulted through two rounds of semi-structured interviews, in which they were asked to provide a critical analysis of the literature review results and validate the brainstorming/mind-mapping that was performed by the author team based on their concrete experience.

Finally, proposals resulting from the process were discussed with representatives from two associative organizations operating within the construction industry in Romania to ensure that they were suitable for the needs of a large number of companies. We believe that the results are also applicable on a European scale.

3. Approaches to Digital Twins

A digital twin is known as a virtual version of a real structure that is used with the aim of achieving advanced simulation results to monitor information through signals from sensors, predict problems and improve decision-making [4]. The use of digital twins has helped to assist researchers and professionals in improving operations, predicting problems and seeking to fix those problems to achieve high quality and reduce costs [5]. Recent trends have shown that digital twins have multiple uses and can be included in all fields and industries, from manufacturing and production processes to the management of engineering and construction projects and healthcare facilities or other complex applications (e.g., in agriculture or retail).

The proper functioning of a digital twin requires both technical capabilities (e.g., sensors, software, actuators) and a good command of the conceptual support methods, such as natural resource management, industrial resource management, technology lifecycles and communication instruments. As studies at Cambridge University have reported that a method in which artificial intelligence can be used to create digital twins to monitor the health status of patients has been found [3], it is expected that improvements and developments in the field will pave the way for digital twins to enter all fields and industries in the near future, bolstered by advanced machine learning applications. The articles [4,5] argue that a digital twin is a dynamic model that contributes to conducting experiments quickly and reducing costs in addition to mitigating expected risks. In another work, the authors point out that digital twins help in the processes of sustainability and smart innovation and enhance the level of occupational safety by providing directly applicable best practices [6].

Another perspective regarding digital twins helping to discover strategic opportunities and options for many disciplines is that they contribute toward mitigating potential liabilities and save costs during the process of testing options on complex and expensive real entities, such as a building, land transportation infrastructure, manufacturing equipment, etc. [7]. The same author remarks that digital twins have also become of commercial value, can be used to achieve sustainability and can improve the quality of people's lives by leveraging the accomplishment of goals in these areas. The writer also considers it noteworthy that digital twins are an important and growing part of performance management strategies for companies and that they are increasingly contributing to reductions in risks [7].

4. Advantages and Uses of the Digital Twin

A digital twin can be designed and enacted when the physical system has the capabilities that help to provide complete data through which the digital twin can create and maintain a virtual system that simulates the physical system in real time and provides feedback for the received data [8]. The digital copy enables the analysis of the behavior of the real world system and thus, modifications and improvements can be made to the target activities within the project. At the same time, real events and operational issues, as well as future variables, can also be predicted through the virtual simulation [9].

When the digital twin achieves the flexibility of exchanging data and decisions in both directions, it can then correctly predict and mitigate complex system behaviors and technical malfunctions, in addition to external influences on the system, in due time [10].

Digital twins have a considerable number of advantages and uses:

- They can ensure and verify the integrity of a system model by conducting tests using data from the operating environment and then realizing evaluations, improvements and predictions;
- They can assist decision-makers in supporting their decisions based on reports provided by the digital system regarding the project to be implemented in the real environment;
- They can predict future changes in the physical system as the digital system provides the ability to analyze and simulate operations so that proper plans can be prepared;
- Through simulation, they can discover applied opportunities to be added to the physical system, and to any improved versions, as the twin can reveal extended visions and significant gains for the results of the real-world system.

Considering the rapid spread of information technology and the Internet of Things (IoT) and the availability of sensors, communication networks and analytics software, it is now possible to develop digital twin systems in most areas of interest within various fields and industries, including construction project management.

5. The Use of Digital Twins in Construction Management

There is a growing number of projects using digital twins and artificial intelligence in construction industry projects, with studies so far indicating that there are 10 countries that have achieved and published good results, most notably China, the United States of America, the United Kingdom and Australia [11]. In the same study that made use of the VOSviewer software for mapping knowledge and information exchanges [12] and other dedicated platforms, it can also be noticed that some other countries have had mixed experiences in the employment of advanced digital solutions within construction projects, such as Pakistan and New Zealand. On the other hand, a case study from Italy was recently included as an international cooperation example to demonstrate that a comprehensive digital system can be used in construction industry projects [13].

The concept of digital twins appeared as a tool to prepare enhanced management processes and control them through data, and it was initially used in the areas of production, manufacturing and operations management but quickly spread to other sectors that also require big data analytics. Digital twins are used to increase performance, reduce costs, lower potential risks and optimize supply chains for construction sites using artificial intelligence and computer aided engineering [14]. When creating a digital twin, the dimensions of the conceptual space used for the workflow and the correct use of the data and information exchange can facilitate the integration of artificial intelligence techniques [15]. The requirement for construction companies to automate processes, process data at construction sites and understand plans and directions for various project roles predate the emergence of digital twins, but we consider that there is an enhanced possibility that they can be addressed in the present and near future. In order to bridge digital gaps by obtaining a coherent and comprehensive process framework for the design and construction of buildings and other facilities, digital twins for construction projects (DTCP) must therefore be integrable within the architecture of existing construction companies, which are characterized by a dynamic matrix structure that changes with each project and by an increased dependence on local suppliers of expertise, materials and workforce.

According to [16], the most common architecture involves a description of the operations carried out by the equipment, a central control unit that is based on comparing the operating environment to the stored data according to the targeted plans and the concrete results (e.g., the cost calculations, the quality of the design implementation, the speed of delivery, the accuracy in performance, etc.). Thus, starting from the findings in [16], we can surmise that the use of such digital systems can provide improved planning for construction projects and provide site managers with the ability to quickly address specific needs and issues, such as vibration factors, temperature variations, building resistance to wind, costs, implementation time, profits, losses, etc. [17]. DTCPs can predict unexpected events and formulate options for human managers, or even implement them automatically, using real-time artificial intelligence that is based on data stored in its database. By solving malfunctions and providing appropriate solutions to help project management, a digital twin has the ability to facilitate the progress of the implementation process [18].

6. Digital Twins for Construction Projects

6.1. Building Information Modeling (BIM) (Stage 1)

BIM is a well-known approach for managing existing buildings, which includes the procedures and processes that control the workflows in relation to the operation of the unit (utility management, maintenance and repair, monitoring of environmental factors, etc.). BIM platforms conform to digital twin standards of intervention as they have been optimized over the past decade to match the need for technical tools and information with real technical and human-related processes [19,20]. These tools can allow for the management of small- and large-scale facilities by providing virtual operations and "what if" scenarios that underpin future visions and predictions regarding the operational environment [21]. In our approach, we did not intend to go into the details of the operation or maturity of BIM as the literature on this topic is clear and mature, but we considered BIM (however complex it may be) as the first stage in deploying DTCPs, only addressing the part of the lifecycle dedicated to project usage in real situations.

The researchers in [22] describe a classification-based review of the literature addressing the use of digital twins in operational processes, which can be applied, mutatis mutandis, in the case of DTCPs too, as we can consider BIM as an equivalent to the simple digital shadow used in production systems. However, in order to process the integrated building data correctly, the virtual copy depends on the real environment copy [23] more so than in the case of manufacturing equipment, since buildings are not natively digital or based on power usage with embedded electrical signals. Since a digital shadow mainly depends on the one-way flow of data from the operational environment to the virtual environment, the limits of merging data in both directions needs to be considered carefully, as researchers have indicated that some changes can be made to the digital system that should not be applied to the real building and vice versa (usually damaging or unwanted modifications) [24]. This is important for BIM since it is not usually operated by specialists and it needs clearly defined boundaries and protections. A similar approach can be used when using digital tools in the first half of the construction lifecycle, when the building is being created, as it can offer important information for project managers on achieving objectives and avoiding problems and risks that may occur. This can lead to an improved implementation process [25] but does not significantly impact the way in which the facility is conceived.

6.2. Building Control Techniques and Applications (Stage 2)

The components of communication between digital and physical twins are considered to be the most important elements that help when digitalizing operations because they mainly depend on feeding the proper data flowing from the sensors that monitor work status and progress through the monitoring equipment that makes it suitable for digital processing. Construction work is characterized by many staggered and parallel activities and stages, which can be more likely to fall into error, in addition to wasting time and being exposed to risks. This makes real-time sensor data very useful for the virtual solution [3].

As shown in Table 1, some applications can be tested for monitoring activities on a construction site with minimal changes to current practices.

Table 1 shows some activities that can be tracked through electronic/IoT means that highlight the need for monitoring during work and for achievements being measured on site; for example, the movement of workers, the security of the performed tasks, compliance to health and safety procedures, material deliveries, cost management, quality control and the verification of the observance of standards agreed upon in contracts [3]. All of these tasks and tools form the basic map that the Stage 2 digital twin must address in order for it to be impactful and cost-efficient enough to warrant the upgrading of existing systems and practices. Through these processes, various project management functions can be supported in monitoring the progress and course of the execution of work, comparing the work to the plans, identifying problems and addressing those problems in a timely fashion and in a manner that serves the interests of the beneficiaries through the use of human intervention or equipment-based actuation.

Table 1. The technologies and applications for monitoring a construction site in a Stage 2 Digital Twin (Source: [3] with modifications).

Technique/Data Type	Method Equipment	Example Application
Measurement of distance, location, travel	Telemetry, laser scanning, drone photogrammetry	Recording the status of work/progress on construction sites
GPS, photo/video recordings	GPS positioning, cameras	Track project implementation processes and measure results
Sensors (of all types)	Pressure, temperature, weight, vibration, humidity, lighting, acceleration, tilt	Assess and monitor levels of quality, occupational safety and environmental impact and ensure the optimal operation of equipment
Communication networks	Wi-Fi, cellular, LoRaWAN/SigFox	Assess and monitor material, location of the workers, safety issues and transit times
Audio and sonar	Microphones	Identify equipment malfunction and perform predictive maintenance
Medical and health sensors	Temperature, pulse, respiration rate, blood pressure	Ensure and maintain the optimal performance of human workers, prevent injuries, infections, etc.

6.3. The Development of Digital Twins for Construction Projects—DTCP (Stage 3)

In the approach discussed in this paper, the digital twins for construction projects (DTCP) that we propose are considered to be an improvement on both the BIM framework and the monitoring and actuation digital twins that were described in the two previous stages. The third generation represents a stable implementation stage that benefits from advanced knowledge and the correct employment of complex technologies, such as artificial intelligence and deep learning, as well as data mining and the ability to perform contextual analyses as defined by [26]. Despite reviewing many new studies and research, discussions are still missing regarding the creation of digital twins that are capable of completely managing the activities and stages of a construction or reaching a comprehensive pattern for construction management, fully autonomous solutions and detailed customizations for the construction industry.

In Figure 1, our proposed framework is represented, including the work environment activities that can be translated into a digital system that can control the implementation process by setting up performance measurements for the elements on which the project depends. As the elements within the virtual application are those that control the elements of the physical environment, these two processes can be connected using cyber-physical systems that combine sensorics, actuation and independent decision-making software. The sensors monitor and follow the progress of activities and power the knowledge base with information received as input from the real world (movements, quantities, sounds, actions, etc.). They communicate this through the intermediary of the IoT (local networks, cloud solutions, cybersecurity filters, etc.) to the database that has the ability to compare the information to the stored plans and generate decisions based on any differences or problems that they may be faced by the work site. During the implementation of the project activities on the construction site (starting from its objectives and ending at its KPIs), the digital system monitors the costs and progress of work completion by tracking results with respect to forecasts. The system makes decisions or, in extreme cases, informs decision-makers through the proper modeling and simulation (including graphical and virtual reality capabilities) of predictions that may become reality and influence the course of the project. Operationally, the entire digital twin system can function by integrating a set of simple and direct task applications (e.g., site monitoring, team assignments and tracking, equipment maintenance planning, material flow analysis, etc.) within a cohesive platform. In this way, an increased robustness can be achieved with less software development work and greater flexibility for the company running the construction site.

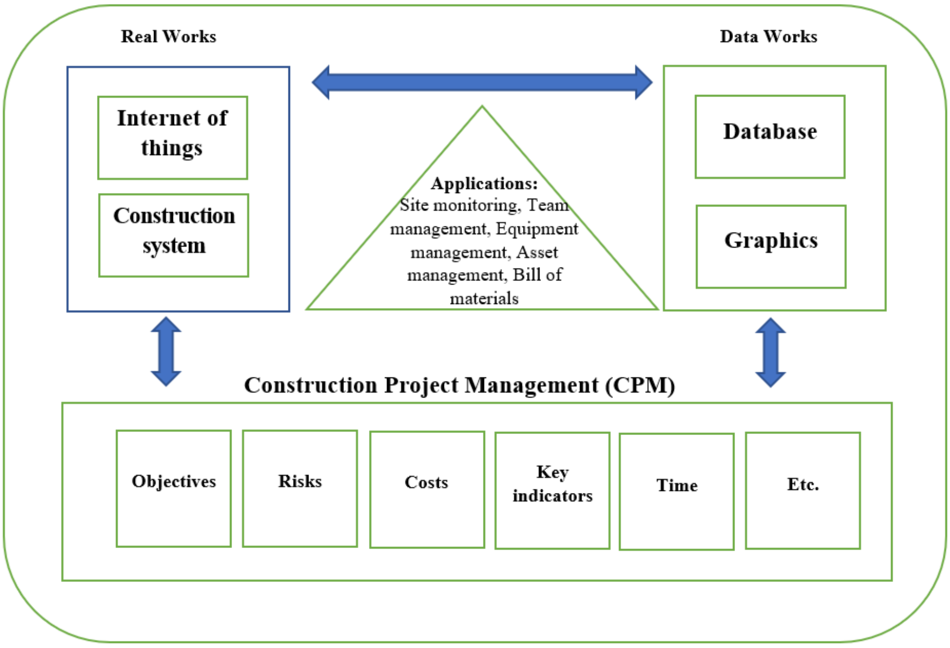

Figure 1. Digital twins for construction projects (DTCP) model, Stage 3.

The digital twin system can support performance data gathering and the monitoring of operational processes through the automatic scanning of each sub-system, and it only requires human intervention in the case of complex situations that cannot be programmed as scenarios (e.g., the materialization of risks, environmental factors, any breach of contracts, etc.). In all other situations, costs and speed are optimized in an automated manner [27]. The principle of the operation of the machine-based system depends on feeding it with the proper data that allow it to understand the operations and enable it to perform work in a pre-programmed manner in which accuracy and quality can be controlled [28]. The progress data are linked to working within the operational environment while the progress of the operational processes is followed up and tracked in the real world, so bi-directional communication and the ability to perform parallel work is mandatory [29].

Concerning the technical aspects and the technologies required by a Stage 3 DTCP, study [30] discussed the use of digital twins in manufacturing and highlighted the need to develop adequate cybersecurity mechanisms to protect its components and the data within the system. Article [31] indicated the use of a smart construction approach through smart IoT technologies and recommended the thorough development of communication routines using augmented reality to increase the speed and effectiveness of integrating the real and digital worlds. Finally, study [32] brought concepts related to sustainability into the discussion, which could be resolved by implementing the complete “digital data-driven concept” that was proposed by the authors as an integrative framework. All of these elements support our proposed concept as possible avenues of implementation.

7. Results and Discussion

Through the review of previous studies and research articles, we could conclude that there is significant potential for adapting this concept outside of its native economic sectors. Most researchers believe that digital technology is in a period of rapid and increasing development and that digital twin systems can support many management strategies for companies [7].

Digital twins have many advantages, as indicated by [5], and can be used in various domains, such as the automotive industry, health care, natural resources exploitation, smart cities, etc. However, a significant number of challenges remain for fully digitalized industries, even in fields with more mature results than the construction sector, which range from the visualization of the entire system and its relations to checking the results of the physical model and verifying the correctness of the processes, including operations, safety and maintenance, and the fully developed artificial intelligence that commands the digital model [33–39]. In the same context, digital twins in the construction industry have a lot to learn from similar solutions for other fields in which work cannot stop, such as aviation and aircraft maintenance [33,36–38]. Today, companies implement projects by relying on digital charts and graphs and using data from measuring devices to support project leadership [37], but the visualization options of digital twins that use digital native data are significantly increased, allowing for full immersion and virtually validated decisions. Companies are preparing to introduce digital technology into many industries that are related to construction, such as work site administration, building operation and real estate. Whether by exploiting large databases [33,34,38] or using augmented reality to make sense of collected data, digital twins are considered to be among the tools that can be used in complex decision-making processes, from planning to implementation processes that can be carried out in a timelier manner in construction projects.

Moreover, other domains with successful digital twin implementation, such traffic management and energy consumption monitoring [39,40], demonstrate that a dynamic location, such as a construction site, can be successfully administered by a digital system. So far, many of these overarching objectives have not been implemented for the construction industry, hence the need to define the three-stage approach proposed in this paper.

8. Conclusions

In light of the acceleration of technical and economic progress, the world is moving toward employing technology in all aspects of life and companies are in a state of permanent and rapid development to improve the quality of their services and products. Digital twins have become one of the tools and systems used by industrial companies that can provide many advantages to serve the goals of the organizations. Construction companies, as with their manufacturing counterparts, have significant interest in increasing worker security, profitability, implementation schedules and customer satisfaction. As a consequence, the modern tools and systems that have developed into the digital twin system can find customized application in the construction sector, but they are usually confronted with significant challenges related to delocalized work environments and the specifics of construction project management that emphasize safety, material consumption and deadlines as opposed to the high capability and low variability that occurs in the production sector.

The review of literature that we performed to gain insights into the applications of the associated concepts within the construction sector revealed that researchers have not yet reached a common understanding of the desired features and common pitfalls of the use of digital twins. Standards and common frameworks are still developing and a considerable amount of work is being carried out empirically, with each situation and company developing their own approach. Convergence is probably still a few years away, which leaves room for systematization efforts, such as that performed in the present paper.

For this reason, in the field of construction, a three-stage model is proposed with the well-known BIM approach considered as Stage 1 (as it is already applied on a large scale for lifecycle management that is focused on building utilization), the current monitoring and actuation digital twin model that is used for smart homes and smart cities considered as Stage 2 (which most companies are working towards at the moment) and an envisioned Stage 3 that (almost) completely automates decision-making within a given project on a construction site. This envisioned Stage 3 is called digital twins for construction projects (DTCP), which we consider will be desirable in the future. This approach employs a complete system without the need for human intervention in managing most tasks related to achieving the cost, time and performance objectives of a building project. The authors propose that these objectives can be reached by employing digital twin systems in all components of project implementation, while providing worker and site protection in the real world and information security to maintain the correct flow of data for analytics in the digital world.

Among the limitations of the suggested approach, there is the need to highly customize the combination of applications before its implementation, the cost and trust issues associated with reducing human involvement on construction sites and the possible incompatibilities among its components (technical, managerial or otherwise). It is also important to mention the fact that the construction sector, as we have discussed for the purpose of this research, still has some relevant doubts about the applicability of digital technologies and advanced artificial intelligence-based decision-making in activities that are involved in their usual approach to work, since their work is both highly and complexly regulated and subject to unforeseen circumstances, especially on work sites. We believe that an effort to implement DTCP will not succeed without a large policy dialogue involving the companies, unions and regulating bodies of the construction field.

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References

1. El Jazzar, M.; Piskernik, M.; Nassereddine, H. Digital twin in construction: An empirical analysis. In Proceedings of the EG-ICE 2020 Workshop on Intelligent Computing in Engineering, Online, 1–4 July 2020; pp. 501–510.
2. Campos-Ferreira, A.E.; de Lozoya-Santos, J.J.; Vargas-Martınez, A.; Mendoza, R.R.; Morales-Menendez, R. Digital Twin Applications: A Review. *Mem. Del Congr. Nac. Control Autom.* **2019**, *2*, 606–611.
3. Sacks, R.; Brilakis, I.; Pikas, E.; Xie, H.; Girolami, M. Construction with digital twin information systems. *Data-Cent. Eng.* **2020**, *1*, e14. [CrossRef]
4. Schöberl, M.; Kalla, T.; Sauermann, T.; Rimböck, F.; Kessler, S.; Fottner, J. The Process-Oriented Digital Twin of Construction Machinery. In *8. Fachtagung Baumaschinentechnik*; Technische Universität München: Munich, Germany, 2020; pp. 203–214. Available online: https://mediatum.ub.tum.de/doc/1577913/file.pdf (accessed on 11 January 2022).
5. McCausland, T. Digital Twins. *Res.-Technol. Manag.* **2021**, *65*, 69–71. [CrossRef]
6. Pushkar, P.; Costa, S. The Digital Twin Opportunity. *MIT Sloan Management Review*, 11 August 2021. Available online: https://sloanreview.mit.edu/article/the-digital-twin-opportunity/ (accessed on 11 January 2022).
7. Parris, C. Four Ways Digital Twins Can Drive Industrial Innovation. *Forbes*, 11 December 2020. Available online: https://www.forbes.com/sites/forbestechcouncil/2020/12/11/four-ways-digital-twins-can-drive-industrial-innovation/ (accessed on 13 January 2022).
8. Madni, A.M.; Madni, C.C.; Lucero, S.D. Leveraging digital twin technology in model-based systems engineering. *Systems* **2019**, *7*, 7. [CrossRef]
9. Madni, A.M. Expanding Stakeholder Participation in Upfront System Engineering Through Storytelling in Virtual Worlds. *Syst. Eng.* **2015**, *18*, 16–27. [CrossRef]
10. Madni, A.M.; Spraragen, M.; Madni, C.C. Exploring and Assessing Complex System Behavior through Model-Driven Storytelling. In Proceedings of the IEEE Systems, Man and Cybernetics International Conference, Invited Special Session "Frontiers of Model Based Systems Engineering", San Diego, CA, USA, 5–8 October 2014; pp. 1008–1013. [CrossRef]
11. Darko, A.; Chan, A.P.C.; Adabre, M.A.; Edwards, D.J.; Hosseini, M.R.; Ameyaw, E.E. Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities. *Autom. Constr.* **2020**, *112*, 103081. [CrossRef]
12. Van Eck, N.J.; Waltman, L. *VOSviewer Manual*; Univeristeit Leiden: Leiden, The Netherlands, 2013; Available online: https://www.vosviewer.com/documentation/Manual_VOSviewer_1.5.4.pdf (accessed on 25 January 2022).
13. Angjeliu, G.; Coronelli, D.; Cardani, G. Development of the simulation model for Digital Twin applications in historical masonry buildings: The integration between numerical and experimental reality. *Comput. Struct.* **2020**, *238*, 106282. [CrossRef]

14. Barykin, S.Y.; Bochkarev, A.A.; Dobronravin, E.; Sergeev, S.M. The place and role of digital twin in supply chain management. *Acad. Strateg. Manag. J.* **2021**, *20*, 1–19.
15. Toorajipour, R.; Sohrabpour, V.; Nazarpour, A.; Oghazi, P.; Fischl, M. Artificial intelligence in supply chain management: A systematic literature review. *J. Bus. Res.* **2021**, *122*, 502–517. [CrossRef]
16. Porter, M.E.; Heppelmann, J.E. How Smart, Connected Products Are Transforming Companies. *Harv. Bus. Rev.* **2015**, *93*, 96–114.
17. Schweigert-Recksiek, S.; Trauer, J.; Engel, C.; Spreitzer, K.; Zimmermann, M. Conception of a Digital Twin in Mechanical Engineering—A Case Study in Technical Product Development. In Proceedings of the Design Society: DESIGN Conference, San Francisco, CA, USA, 16–19 January 2020; Volume 1, pp. 383–392. [CrossRef]
18. Wilberg, J.; Kalla, T.; Fetscher, M.; Rimbock, F.; Hollauer, C.; Omer, M. Development of a Use Phase Data Strategy for Connected Products: A Case Study in Industry. In Proceedings of the 2018 Portland International Conference on Management of Engineering and Technology (PICMET), Honolulu, HI, USA, 19–23 August 2018; pp. 1–12. [CrossRef]
19. Rodionov, N.; Tatarnikova, L. Digital twin technology as a modern approach to quality management. In *E3S Web of Conferences*; EDP Sciences: Les Ulis, France, 2021; Volume 284, p. 04013.
20. Hu, Z.-Z.; Tian, P.-L.; Li, S.-W.; Zhang, J.-P. BIM-based integrated delivery technologies for intelligent MEP management in the operation and maintenance phase. *Adv. Eng. Softw.* **2018**, *115*, 1–16. [CrossRef]
21. Makarov, V.V.; Frolov, E.B.; Parshina, I.S.; Ushakova, M.V. The Concept of Developing a Digital Twin. 2019. Available online: https://mlsd2019.ipu.ru/proceedings_1/section_15/1252-1254.pdf (accessed on 15 January 2022).
22. Kritzinger, W.; Karner, M.; Traar, G.; Henjes, J.; Sihn, W. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC Pap.* **2018**, *51*, 1016–1022. [CrossRef]
23. Sidani, A.; Dinis, F.M.; Duarte, J.; Sanhudo, L.; Calvetti, D.; Baptista, J.S.; Martins, J.P.; Soeiro, A. Recent tools and techniques of BIM-Based Augmented Reality: A systematic review. *J. Build. Eng.* **2021**, *42*, 102500. [CrossRef]
24. Khajavi, S.H.; Motlagh, N.H.; Jaribion, A.; Werner, L.C.; Holmstrom, J. Digital Twin: Vision, Benefits, Boundaries, and Creation for Buildings. *IEEE Access* **2019**, *7*, 147406–147419. [CrossRef]
25. Nassereddine, H.; Veeramani, D.; Hanna, A. Augmented Reality-Enabled Production Strategy Process. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction, Banff, AB, Canada, 21–24 May 2019; pp. 297–305. [CrossRef]
26. Gurevich, U.; Sacks, R. Longitudinal study of BIM adoption by public construction clients. *J. Manag. Eng.* **2020**, *36*, 05020008. [CrossRef]
27. Becue, A.; Maia, E.; Feeken, L.; Borchers, P.; Praca, I. A new concept of digital twin supporting optimization and resilience of factories of the future. *Appl. Sci.* **2020**, *10*, 4482. [CrossRef]
28. Lin, W.D.; Low, M.Y.H. Concept design of a system architecture for a manufacturing cyber-physical digital twin system. In Proceedings of the 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, 14–17 December 2020; pp. 1320–1324.
29. Gehrmann, C.; Gunnarsson, M. A digital twin based industrial automation and control system security architecture. *IEEE Trans. Ind. Inform.* **2019**, *16*, 669–680. [CrossRef]
30. Leng, J.; Zhou, M.; Xiao, Y.; Zhang, H.; Liu, Q.; Shen, W.; Su, Q.; Li, L. Digital twins-based remote semi-physical commissioning of flow-type smart manufacturing systems. *J. Clean. Prod.* **2021**, *306*, 127278. [CrossRef]
31. Hasan, S.M.; Lee, K.; Moon, D.; Kwon, S.; Jinwoo, S.; Lee, S. Augmented reality and digital twin system for interaction with construction machinery. *J. Asian Archit. Build. Eng.* **2021**, 1–12, Ahead-of-print. [CrossRef]
32. Mêda, P.; Calvetti, D.; Hjelseth, E.; Sousa, H. Incremental Digital Twin Conceptualisations Targeting Data-Driven Circular Construction. *Buildings* **2021**, *11*, 554. [CrossRef]
33. Xiong, M.; Wang, H.; Fu, Q.; Xu, Y. Digital twin–driven aero-engine intelligent predictive maintenance. *Int. J. Adv. Manuf. Technol.* **2021**, *114*, 3751–3761. [CrossRef]
34. Zambal, S.; Eitzinger, C.; Clarke, M.; Klintworth, J.; Mechin, P.Y. A digital twin for composite parts manufacturing: Effects of defects analysis based on manufacturing data. In Proceedings of the 2018 IEEE 16th International conference on industrial informatics (INDIN), Porto, Portugal, 18–20 July 2018; pp. 803–808. [CrossRef]
35. Cityzenith. What Are Digital Twins? *What the Building and Real Estate Industries Need to Know. Cityzenith, 9 October 2018.* Available online: https://cityzenith.com/post/what-are-digital-twins-building-real-estate-industries (accessed on 15 January 2022).
36. Shirowzhan, S.; Tan, W.; Sepasgozar, S.M. Digital twin and CyberGIS for improving connectivity and measuring the impact of infrastructure construction planning in smart cities. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 240. [CrossRef]
37. West, T.D.; Blackburn, M. Is Digital Thread/Digital Twin Affordable? A Systemic Assessment of the Cost of DoD's Latest Manhattan Project. *Procedia Comput. Sci.* **2017**, *114*, 47–56. [CrossRef]
38. Uhlemann, T.H.-J.; Lehmann, C.; Steinhilper, R. The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0. *Procedia CIRP* **2017**, *61*, 335–340. [CrossRef]
39. Kumar, S.A.; Madhumathi, R.; Chelliah, P.R.; Tao, L.; Wang, S. A novel digital twin-centric approach for driver intention prediction and traffic congestion avoidance. *J. Reliab. Intell. Environ.* **2018**, *4*, 199–209. [CrossRef]
40. Negri, E.; Fumagalli, L.; Macchi, M. A Review of the Roles of Digital Twin in CPS-based Production Systems. *Procedia Manuf.* **2017**, *11*, 939–948. [CrossRef]