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POTENTIAL USE OF DIGITAL TWIN FOR CONSTRUCTION PROGRESS MONITORING

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ABSTRACT

The digital twin (DT) presents an opportunity for the integration of the physical world into the digital world. DT technology has the potential to transform the construction industry and respond to some of its challenges. In conventional construction projects, progress is largely monitored by direct observation and measurement which suffers from numerous challenges, including low productivity, blunders, and poor technology advancements. Concerns are now being raised about integrating technology for autonomously monitoring building activity. In other sectors, DT technology has been responsible for saving product development time and costs by up to 50%. However, DT is still lagging the adoption of new technologies in the construction industry. The overarching aim of this study was to explore the adaptability of DT in construction site progress monitoring. This study comprehensively reviews and analyses DT concepts, technologies, and applications in the construction industry, parameters of applications of DT in construction site progress monitoring, how DT could be used for site progress monitoring in construction, common challenges in the implementation of DT in site progress monitoring, and strategies such as barriers related to DT in site progress monitoring, using literature findings while incorporating qualitative analysis of semi-structured interviews. This research shows that DT has a high potential to solve the numerous challenges in construction site progress monitoring, rather than other current technologies in use. Thus, this study raises awareness and the need for the application of DT in construction site progress monitoring.

Keywords: *Automation; Construction Industry; Digital Twin; Site Progress Monitoring.*

1. INTRODUCTION

The construction industry is infamous for the long-standing issue of poor performance and has been criticised for resistance to adopting technological advancements (Akanmu et al., 2021). However, evidence from the manufacturing sector and other industrial sectors has sparked an interest in construction to adopt technological advancements (Fischer et al., 2023). The exponential growth of data-acquisition systems, information technology, and networking technologies has enabled the synergistic integration with building lifecycle providing real-time monitoring and more control over project outcomes (Akanmu & Anumba, 2015). These technologies have fostered some of the emerging fields such as Virtual Design and Construction (VDC), Cyber-Physical Systems (CPS)

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and Digital Twins (DTs) which facilitate the automation of construction processes worldwide (Akanmu et al., 2021; Rafsanjani & Nabizadeh, 2023).

The applications of these new developments share many similarities, VDC is a broad area which focuses on using multidisciplinary performance models of construction projects to support various project objectives (Rafsanjani & Nabizadeh, 2023). On the other hand, DTs seek to enable two-way dynamic mapping between virtual models and physical components (Tao et al., 2019) while CPS focus on providing real-time monitoring and active control via communication and computing (Liu et al., 2018). Akanmu et al., (2021) identified DT as a prerequisite for the development of a CPS.

Despite being a 20-year-old concept, the notion of a Digital Twin was first introduced in 2003 in a Product Lifecycle Management course (Grieves, 2014). DT was first characterised as “a reengineering of structural life pre-diction and management” (Tuegel, 2012), before moving on to product manufacturing (Boschert et al., 2016) and more recently, smart cities (Howell et al., 2017). DT has been successfully used in several fields, including product design, production, prognostics, and health management (Tao et al., 2019). It expands on the foundations of computing in construction, construction monitoring technologies and methodologies, and lean planning and control. Digital twins provide a conceptual link between these strands for a closed-loop production control system (Sacks et al., 2020).

Rafsanjani and Nabizadeh (2023) state that the construction sector often has bottlenecks, slowing operations without supervisors' knowledge. In traditional construction, progress is monitored mainly by direct observation, and measurement consumes considerable time and produces errors (Costin et al., 2012; Zhao et al., 2019). Many technology methods for autonomously monitoring building activity have lately been available and widely implemented (Sacks et al., 2020). Many authors including Akanmu et al., (2021) and Fischer et al., (2023) have identified these technological advancements as the solution for the long-standing poor performance of construction industry based on the success they have had on other industries. Engineers can use real-time mirroring to forecast and avoid mechanical failures, and it helps manufacturers make better forecasts, choices, and strategies (Guo et al., 2022). Therefore, this research attempts to study the potential of using DT technology to facilitate construction progress monitoring. This paper initially reviews the concept of DT and determines its application of DT in the construction industry. Subsequently, semi-structured interviews were conducted among industry professionals and research scholars to identify how DT can be adopted for construction progress monitoring and potential barriers to its adoption.

2. LITERATURE REVIEW

The DT is such a new technology, that its definitions and abilities are not yet well understood on a systematic level. Consequently, standards and best practices for applications have not yet been clearly defined (Ibrahim, 2019). According to Glaessgen and Stargel (2012) and Negri et al. (2017), NASA had initially defined DT as a probabilistic simulation of a system that employs the physical models. A more common definition was brought by Kritzinger et. al., (2018) who defined DT as the virtual and computerised counterpart of a physical system. Reifsnider and Majumdar (2013) defined DT as Physical simulations of the materials and structures considering the engineering sector while Lee, et. al., (2013) defined DT as models of the process's current state and behaviour. Therefore, being a relatively new concept, definitions and applications of DT had been industry-specific. However, all definitions refer to a digital counterpart of a physical system as explained by Kritzinger et. al., (2018).

DTs have a brief history, which is mostly due to technological constraints during their early development. The first occurrence of DTs may date back to Grieves' 2003 presentation, which was regarded to be the origin of DTs (Grieves, 2014). Theoretically, DTs developed in three stages: formation, incubation, and growth (Tao et al., 2019). From the inception of the DT concept in 2003 to 2011 is identified as the formation stage where a rapid advancement of communication technology was observed. In 2011, NASA established the description of DTs and discussed its potential use in the aviation industry making the beginning of the incubation period (Glaessgen & Stargel, 2012). From 2014, DT has experienced rapid growth with increased attention from academics (Tao et al., 2019).

2.1 ARCHITECTURE OF DIGITAL TWIN

Sensor and measurement technologies, the Internet of Things, and machine learning provide the foundation of the digital twin's architecture (Liu et al., 2018). The primary purpose of implementing a digital twin using physics-based models and data-driven analytics is to offer realistic operational representations of the assets (Farsi et al., 2019). The technology enables simulations on the digital twin to anticipate the actual product's behaviour. The accuracy of the digital twin grows as the number of simulations and equipment linked to the network increases (Boschert, et, al., 2016).

2.2 CHARACTERISTICS OF DIGITAL TWIN

Depending on the type of DT, it can possess distinctive properties from others, but regardless, all DTs have a few characteristics in common as presented in the table below.

Table 1 Characteristics of digital twin

Characteristics	Description
High-fidelity	A DT must be an almost replica of its physical counterpart in terms of look, content, functioning, and so on. Computer models with extremely high fidelity are regarded as the DT's backbone (Reifsnider & Majumdar, 2013).
Dynamic	Create connection and interchange between the physical and virtual worlds. The data transferred may be dynamic, historical static, or descriptive static (Barricelli et al., 2019).
Self-evolving	A DT self-adapts and self-optimises based on the data acquired in real-time by its physical twin (Barricelli et al., 2019).
Identifiable	DT could be uniquely recognised from its physical twin or vice versa everywhere in the world and throughout its lifespan (Tao et al., 2019).
Multiscale and Multi physical	The virtual model in DT is based on the physical twin's macroscopic geometric features, such as shape, size, tolerance, and so on, as well as microscopic properties, such as surface roughness (Singh et. al, 2021).
Multidisciplinary	DT serves as the pillar of Industry 4.0, bringing together computer science, information technology, and communications; mechanical, electrical, electronic, and mechatronic engineering; automation and industrial engineering; and system integration physics, to name a few (Bajaj et al., 2016).

Hierachy	The hierarchical aspect of DT stems from the fact that each of the various components and elements that constitute the final product has its own DT model (Tuegel, 2012).

2.3 BENEFITS OF DIGITAL TWIN

The primary advantages of DT technology are its ability to reduce mistakes, uncertainty, inefficiencies, and costs in any system or process. Additionally, it dismantles the silos that exist inside typical industrial compartmentalised and divided systems. Numerous purported advantages of DT are presented in the table 2.

Table 2 Benefits of digital twin

Benefit	Description	Source
Predicting Problems/ System planning	Real-time data exchange between the physical asset and its DT is capable of anticipating issues at various phases of the product's lifespan.	(Tao, et al., 2019), (Guo et al., 2022)
Prototyping	Resulting in faster and more efficient prototyping and re-design.	(Liu et al., 2019).
Cost-effective	The overall cost of prototyping is reduced over time with extensive use of virtual resources.	(Grieves, 2014).
Accessibility	Remote monitoring and management of equipment and systems where local access is restricted.	(Shen et al., 2020)
Improved Maintenance	Traditional maintenance relies on heuristics and worst-case scenarios rather than specific materials, structural configurations, and usages.	(Singh et al. 2021), (Guo et al., 2022)
Documentation and Communication	DT enables a deeper understanding of system responses, it may be used to document and convey the physical twin's behavior	(LaGrange, 2019)
Safer than the Physical Counterpart	The potential of DT to remotely access its physical counterpart, along with its predictive capabilities, can help minimize the possibility of accidents and hazardous breakdowns.	(Goasduff, 2021), (Fischer et al., 2023)
Training	DT could be utilized to create more effective and illustrative safety training programs than conventional methods.	(Kaarlela et al., 2020).
Waste Reduction	Using DT to virtualize and test prototypes minimizes waste, costs, and time spent on developing a product before it is ready for market.	(Singh et al. 2021).

2.4 DIGITAL TWIN IN CONSTRUCTION

The definition of Digital Twin might seem similar to BIM, construction researchers highlighted the differences between these two concepts. As mentioned by Khajavi et al. (2019), the objective, technology, end-users, and facility life stage of BIM and Digital Twin are all unique. While architects/engineers use BIM to do conflict detection and material take-off during the design phase of a project, contractors utilize it for production control, constructability analysis, and site and safety management (Volk et al., 2014). It is incompatible with real-time data (Khajavi et al., 2019). However, the digital twin is used to monitor the physical asset and optimize its operating efficiency through the analysis of real-time information (Khajavi et al., 2019). The data acquired through the deployment of a Digital Twin throughout the facility's operation and maintenance phase could be kept in a database for future projects by architects (Qi and Tao, 2018). The existing literature on Digital Twins in construction is difficult to find since the phrase "Digital Twin" is rarely used directly and is frequently referred to as BIM or BIM-FM (BIM based Facility Management System) (Jazzar et al., 2020).

2.5 AUTOMATION IN PROGRESS MONITORING

Progress Monitoring involves periodic measurement of the actual progress of a project and its comparison with expected progress (Hwang et al., 2013). Successful project progress monitoring requires accurate and efficient capture, analysis, and visualization of project as-built status. Due to the complexity of goals and interdependency of activities, progress monitoring is regarded as one of the most challenging tasks (Alizadehsalehi & Yitmen, 2019). According to Navon and Sacks (2007), the most cost-effective and efficient method of monitoring the progress and performance of building projects is to automate the process. Until now, academics have examined a variety of developing field data gathering technologies for automating project inspections, either through the use of a single technology or through the integration of many technologies (Alizadehsalehi & Yitmen, 2016; Asadi et al., 2021; Rasoolinejad et al., 2020). However, collecting, storing, analyzing, and managing this massive and complex data in order to generate simple, accurate, fast, and real-time progress monitoring reports requires a smart/intelligent system that can incessantly learn and update itself from numerous sources (Boje et al., 2020).

2.6 DIGITAL TWIN IN CONSTRUCTION PROGRESS MONITORING

DT is used to create the optimum solution from detailed simulations and rich data that specify the best architecture, configuration, materials, and cost (Kan & Anumba, 2019). A DT can be used in the build phase to provide the construction specifications or parametric estimates to different providers (Shirowzhan et al., 2020). With enough sensors, the virtual twin is providing all relevant data about the state of the physical twin. During operations, an abundance of data is gathered and transmitted to the DT through a digital thread. DT can discover and even forecast maintenance difficulties in advance (Boje et al., 2020).

2.7 THE NOVELTY OF THIS RESEARCH

DT being a novel approach, there is a lack of clarity on the value that it may offer to individuals, businesses, and industries. Inadequate technical and practical understanding also impedes the advancement of technology (Singh et. al., 2021). Additionally, there is a dearth of case studies illustrating successful practices or business models for integrating DT into company activities (Simchenko *et al.*, 2019). Hence, there is a necessity to investigate the potential of the Digital Twin in the construction industry to assist the project monitoring and controlling process. Finding suitable solutions and potential challenges is also essential to ensuring the better adoption of the DT. Consequently, the need for such an investigation is duly recognized in construction site progress monitoring.

3. RESEARCH METHODOLOGY

Being a novel concept of technology, to explore the potential of DT in construction progress monitoring a qualitative approach was adopted. Hence, the data collection has been done by taking semi-structured interviews with industry practitioners and research scholars who are familiar with the applications of DT. A heterogeneous purposive sampling method was used to select respondents having more than 2 years of working experience in SMART construction from Australia, Singapore, Ghana, China, and UAE. The sample selected includes participants from different age categories. It was also possible to get ideas based on their various experience levels. Face-to-face semi-structured interviews were conducted on online platforms for 30-45 minutes. Collected data were analysed with manual content analysis as the responses varied depending on the scope of involvement with the technology. The profile of the interviewees is presented in table 3 below.

Table 3 Profile of the interviewees

No	Details				
	Designation	**Type of Organization**	**Country**	**Experience**	**Key Expertise Areas Related**
I.01	PhD Researcher	Educational	Australia	4 years	Computer vision, Machine Learning, Image Processing, Deep Learning
I.02	PHD Researcher & Chartered QS	Educational (Currently)	Australia	5 years	Construction Performance measurement, Efficiency and effectiveness in construction
I.03	PHD Researcher	Educational	Australia	4 years	SMART Construction, Construction Industry Skills Research and development in construction
I.04	PHD Researcher & Lecturer	Educational	Australia	6 years	Blockchain, Carbon Emission, Sustainability
I.05	PHD Researcher	Educational	Australia	2 Years	Digital Twin and DT Cities AR, BIM, SMART buildings
I.06	Engineer and Digital Transformer of FM	IT Company	Singapore	2 Years	Digitalizing the typical buildings, BIM
I.07	Facility Engineer	IT Company	UAE	5 years	Digitalizing buildings, BIM
I.08	PHD Researcher	Educational	China	3 Years	Prefabricated Construction, Digitalization Technologies

I.09	PHD Researcher	Educational	Ghana	4 Years	Digital Twin, BIM & SMART buildings
I.10	Professor	Educational	Australia	More than 30 years	Construction Informatics, Construction Data Analytics, Disaster Management,
I.11	Facility Engineer	IT Company	UAE	2 Years	Digitalizing buildings, BIM

Most of the interviewees were from educational organizations because the real-life practitioners of DT in the construction industry are very few. The relevant data is collected from consultancy, facility management, and educational organizations. The type of sample, therefore, provides the research gap with viral information and experience-based and theoretical-based answers.

4. RESEARCH FINDINGS

4.1 AWARENESS OF DT IN CONSTRUCTION SITE PROGRESS MONITORING

Regarding the current level DT application, I.01 held that awareness of the potential use was very low. Respondent further explained that the necessity for the DT is currently used for maintenance work and renovation activities. I.06, I.08, I.09, and I.11 also agreed with this view. All respondents claimed that there is significant potential for DT on the construction industry. According to the interviewees, the industry is trying to visualize and monitor progress through BIM models which have certain limitations with regard to capturing data. I.07 and I.11 stated that partial applications of DT are being used in infrastructure projects and renovation projects where a digital representation of onsite data grant access to areas that would be hard to access.

4.2 ADVANCEMENTS IN DT FOR PROGRESS MONITORING

This section initially aims to distinguish the advancements of DT rather than the current technologies. According to the literature review, there is already discussion about current technologies which are being used in construction site progress monitoring.

The semi-structured interview identified how the DT concept in site progress monitoring differed from the current advanced technologies and the potential of the DT concept in site progress monitoring. The following routine parameters of current automated and semi-automated progress monitoring are identified and suggested.

4.2.1 Project Status Tracking

According to I.04, I.05 and I.10, DT can be used for component tracking, performance monitoring, equipment collaboration tracking and greenhouse gas emission tracking on-site. I.03 explained that *“DT can also help monitor energy consumption and provide strategies to optimize energy usage in building projects”*. Monitoring and tracking other construction activities at the site by avoiding paper-based documentation can be done. Similar observations had been made by Guo et al., (2022) and Fischer et al., (2023).

4.2.2 Site Performance

I.05 stated that *“DT can be used for evaluating the site performance in real-time with the use of previously stored data”*. As the DT gathers information on current progress the data can be compared with previous data to reveal the performance status. According to I.10, *"analysing such data would help take corrective actions to improve the site's current performance"*. These observations further emphasised the findings of Akanmu et al., (2021).

4.2.3 Construction Safety and Health

DT can be used for preventive maintenance and monitored to probably identify any health and safety issues. According to I.04, *"scaffolding erection work can be simulated using the DT before physical erection to ensure the safety of the workers"*. I.05 mentioned that training could be provided for different situations involving augmented and virtual reality with the help of the DT. Hence the interview findings resonated with the concepts brought forward by Akanmu et al., (2021).

4.2.4 Facility Management and Building Performance

I.10 pointed out, *"Facility management has enormous potential, where we have the digital twin of the physical object"*. In I.03's words, A facilities manager's maintenance tasks can be automated in a digital twin model. The system itself, the building, can talk with the digital twin model and give the digital twin model information. Buildings can communicate with actual physical structures.

4.3 CHALLENGES FOR ADOPTION OF DT FOR PROGRESS MONITORING

When considering challenges to adopting DT in site progress monitoring, table 4 lists the challenges identified from the literature along with the interviewees' responses illustrated with shaded background.

Table 4 Identified challenges for the adoption of DT for progress monitoring

Challenges and Factors	I.01	I.02	I.03	I.04	I.05	I.06	I.07	I.08	I.09	I.10	I.11
Investment costs for DT	√	√	√	√	√	√	√	√	√	√	√
System maintenance costs	√	√	√	√	√	√	√	√			√
The need for recruiting IT staff		√	√	√	√	√	√	√	√	√	√
Compatibility of software	√	√	√	√	√			√	√	√	√
Functional possibilities of the system/ Knowledge of the use of DT in the field		√	√	√	√	√			√	√	√
Ability for future upgrading	√		√	√	√			√			
User Experience Readiness and disinterest of users	√	√	√	√	√			√	√	√	
Ability to embrace innovation and change	√	√	√	√	√			√	√	√	
Lack of management support	√	√	√	√	√	√				√	√
Fragmentation of the sector and integration among participants in construction projects	√		√	√	√			√	√	√	√
Time-consuming	√										

Lack of training material, lack of resources for training		√	√	

All interviewees identified the high investment cost as the main barrier to DT technology adoption. I.05 highlights low-cost data collection methods such as drones, photography, and GIS applications, but developing software systems and implementing AR and VR technologies can be expensive. Uncertainty surrounds system maintenance costs due to the evolving nature of DT technology and the lack of standardization. Compatibility issues with other technologies are recognized by I.03 and I.02. DT is a new technology that requires training for staff and faces resistance to change, which I.01, I.02, I.04, and I.09 agreed on. Training, research, and development investments are suggested as solutions. The construction industry is among the least digitized and hesitant to adopt new technologies, but leaders and investors will embrace DT if it improves profitability and efficiency, as stated by I.02, I.08, and I.05. Management support is considered crucial by all respondents, and I.04 emphasized the need for top management support, training, and R&D investments. Due to the industry's fragmentation, digital twin technology can be highly effective and productive. The construction process involves architects, quantity surveyors, civil engineers, and contractors. Simchenko *et al.,* (2019) found time-consuming to be a barrier, which I.03 supports, stating that stakeholders need time to learn about the digital twin concept due to its steep learning curve.

5. CONCLUSIONS AND RECOMMENDATIONS

The main focus of the research was to identify the potential DT technology to improve the progress monitoring of construction projects. The literature findings identified that DT can be considered as a virtual entity, relying on the sensed and transmitted data of the IoT infrastructure with the purpose of allowing optimizations and decision-making. Further, the primary purpose of implementing a DT using physics-based models and data-driven analytics is to offer realistic operational representations of the assets. The literature revealed that there had been promising results with the adaption of DT in sectors other than construction. Common challenges that had influenced the implementation of DT were also identified from the literature. The applicability of these findings to the project progress monitoring was identified through semi-structured interviews. It was revealed that DT can track project status by monitoring component tracking, performance, equipment collaboration, and greenhouse gas emissions on-site. It can also monitor energy consumption and optimize energy usage in building projects. Further, DT enables real-time evaluation of site performance by comparing current progress with stored data, allowing for corrective actions to improve performance. DT also contributes to construction safety and health by simulating and ensuring the safety of workers during activities like scaffolding erection. Lastly, DT facilitates facility management by automating maintenance tasks and allowing buildings to communicate with their digital twin models. Hence, DT technology provides advantages such as risk assessment, predictive maintenance, remote monitoring, improved teamwork, and better decision-making through data analysis and integration. Interviews also revealed fragmented nature, lack of training, time constraints and lack of support from the organization management critical factors in addition to the literature findings. Some of the barriers identified in the literature were rejected by respondents and new barriers were added. ‘Cost’ is identified as a major barrier when it comes to developing countries. It could be noted that the industry does not have a good idea about the barriers due to technology.

Presently, research in the area of DT is at an embryonic stage of development but will be the futuristic option. The research outcomes are contributed to knowledge to understand the DT concepts, developments, and applications of DT in the construction industry. In addition to that the findings also enable comprehension of the barriers for the DT adoption in construction Site progress monitoring. The current study can provide practitioners with a readily accessible point of reference that captures the state-of-the-art of research on the use of digital twins in construction site progress monitoring, as well as the concept, stakeholders, and technologies. In such a context, practitioners can employ the findings of this study as a prior introductory guide. Since construction projects are heterogeneous, more concern needs to be taken on the cost and security of system adoption. Moreover, practitioners should develop innovative attitudes and flexibility to adopt new practices such as the identification of inefficiencies with real-time data, proactive maintenance, and prediction of resilience with futureproofing. These studies can achieve maximum benefit.

However, it shall be noted that given the embryonic stage of development of the DT in construction majority of the interviewees selected for the study had an academic background therefore future research can focus on exploring the practical applications of DT in construction project progress management. Additionally, the newly identified competencies highlighted in this study, as well as any future competencies, need to be firmly established within the construction industry.

6. REFERENCES

Akanmu, A. A., Anumba, C. J., & Ogunseiju, O. O. (2021). Towards next generation cyber-physical systems and digital twins for construction. *Journal of Information Technology in Construction (ITcon), 26*(27), 505–525. https://doi.org/10.36680/j.itcon.2021.027

Alizadehsalehi, S., & Yitmen, I. (2019). A concept for automated construction progress monitoring: Technologies adoption for benchmarking project performance control. *Arabian Journal for Science and Engineering, 44*(5), 4993–5008. https://doi.org/10.1007/s13369-018-3669-1

Asadi, K., Haritsa, V. R., Han, K., & Ore, J.-P. (2021). Automated object manipulation using vision-based mobile robotic system for construction applications. *Journal of Computing in Civil Engineering, 35*(1), 04020058. https://doi.org/10.1061/(asce)cp.1943-5487.0000946

Bajaj, M., Cole, B., & Zwemer, D. (2016). Architecture to geometry: integrating system models with mechanical design. In *AIAA SPACE 2016, Long Beach, California*. https://doi.org/10.2514/6.2016-5470

Barricelli, B., Casiraghi, E., & Fogli, D. (2019). A survey on digital twin: definitions, characteristics, applications, and design implications. *IEEE Access 2019*. *7*, 167653-167671. https://doi.org/10.1109/ACCESS.2019.2953499

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic construction digital twin: directions for future research. *Automation in Construction, 114,* 103179. https://doi.org/10.1016/j.autcon.2020.103179

Boschert, S., Rosen, R., Hehenberger, P., & Bradley, D. (2016). Digital twin—the simulation aspect. *In Mechatronic Futures* (pp. 59-74). Cham: Springer International Publishing.

Costin, A., Pradhanga, N., & Teizer, J. (2012). Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project. *Automation in Construction 24*, 1-15. https://doi.org/10.1016/j.autcon.2012.02.015

Farsi, M., Daneshkhah, A., Hosseinian-Far, A., & Jahankhani, H. (2020). Digital twins and smart cities. In M. Kaur, V. Mishra, & P. Maheshwari (Eds.), *Digital Twin Technologies and Smart Cities* (pp. 5-6). Germany; Springer.

Fischer, A., Beiderwellen Bedrikow, A., Tommelein, I. D., Nübel, K., & Fottner, J. (2023). From activity recognition to simulation: the impact of granularity on production models in heavy Civil Engineering. *Algorithms*, *16*(4), 212. https://doi.org/10.3390/a16040212

Goasduff, L. (2020, October 29). *Gartner survey reveals 47% of organizations will increase investments in IoT despite the impact of COVID-19*. Gartner. https://www.gartner.com/en/newsroom/press-releases/2020-10-29-gartner-survey-reveals-47-percent-of-organizations-will-increase-investments-in-iot-despite-the-impact-of-covid-19-

Glaessgen, E., & Stargel, D. (2012). The digital twin paradigm for future NASA and U.S. Air Force vehicles. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii*, 23-26 April 2012. (pp.1818). https://doi.org/10.2514/6.2012-1818.

Grieves, M. (2014). Digital twin: Manufacturing excellence through virtual factory replication; *White paper, 1, 1-7.* http://www.apriso.com/library/Whitepaper_Dr_Grieves_DigitalTwin_ManufacturingExcellence.php

Guo, C., Xu, X., Hu, J., Zhang, J., & Zhou, Z. (2022). Intelligent design and construction coordination of nuclear power based on digital twin. In *Proceedings of the 3rd International Conference on Green Energy, Environment and Sustainable Development* (GEESD2022) (pp. 144–153). IOS Press. https://doi.org/10.3233/ATDE220276

Howell, S., Rezgui, Y., Hippolyte, J.-L., Jayan, B., & Li, H. (2017). Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources. *Renewable and Sustainable Energy Reviews*, *77*, 193-214. https://doi.org/10.1016/j.rser.2017.03.107

Hwang, B.-G., Zhao, X., & Ng, S. Y. (2013). Identifying the critical factors affecting schedule performance of public housing projects. *Habitat International*, *38*, 214–221. https://doi.org/10.1016/j.habitatint.2012.06.008

Jazzar, E.LM., Piskernik, M., & Nassereddine, H. (2020). Digital twin in construction: An empirical analysis. In *EG-ICE 2020 Workshop on Intelligent Computing in Engineering, Proceedings* (pp. 501-510).

Kaarlela, T., Pieskä, S., & Pitkäaho, T. (2020). Digital twin and virtual reality for safety training. In *Proceedings of the 2020 11th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*, (pp. 115-120). IEEE. https://doi.org/10.1109/CogInfoCom50765.2020.9237812

Kan, C. and Anumba, C. (2019), Digital twins as the next phase of cyber-physical systems in construction, In *ASCE International Conference on Computing in Civil Engineering 2019.* (pp. 256-264). American Society of Civil Engineers. doi: 10.1061/9780784482438.033.

Khajavi, S., Motlagh, N., Jaribion, A., Werner, L., & Holmstrom, J. (2019). Digital twin: vision, benefits, boundaries, and creation for buildings. *IEEE Access*, *7*, 147406-147419. https://doi.org/10.1109/ACCESS.2019.2946515

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, *51*(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

LaGrange, E. (2019). Developing a digital twin: the roadmap for oil and gas optimization. In *Proceedings of the SPE Offshore Europe Conference and Exhibition*. *Aberdeen, UK*. https://doi.org/10.2118/195790-MS

Lee, J., Lapira, E., Bagheri, B., & Kao, H. (2013). Recent advances and trends in predictive manufacturing systems in big data environment. *Manufacturing Letters*, *1*(1), 38–41. https://doi.org/10.1016/j.mfglet.2013.09.005

Liu, Q., Zhang, H., Leng, J., & Chen, X. (2019). Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system. *International Journal of Production Research*, *57*(12), 3903–3919. https://doi.org/10.1080/00207543.2018.1471243

Liu, Z., Meyendorf, N., & Mrad, N. (2018). The role of data fusion in predictive maintenance using digital twin. *AIP Conference Proceedings*. AIP Publishing. https://doi.org/10.1063/1.5031520

Navon, R., & Sacks, R. (2007). Assessing research issues in automated project performance control (APPC). *Automation in Construction*, *16*(4), 474–484. https://doi.org/10.1016/j.autcon.2006.08.001

Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twin in CPS-based production systems. *Procedia Manufacturing, 11,* 939-948. https://doi.org/10.1016/j.promfg.2017.07.198

Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison. *IEEE Access* 6, 3585-3593. https://doi.org/10.1109/ACCESS.2018.2793265

Rafsanjani, H. N., & Nabizadeh, A. H. (2023). Towards digital architecture, engineering, and construction (AEC) industry through virtual design and construction (VDC) and digital twin. *Energy and Built Environment*, *4*(2), 169–178. https://doi.org/10.1016/j.enbenv.2021.10.004

Rasoolinejad, M., Dönmez, A. A., & Bažant, Z. P. (2020). Fracture and size effect suppression by mesh reinforcement of concrete and justification of empirical shrinkage and temperature reinforcement in design codes. *Journal of Engineering Mechanics*, *146*(10), 04020120. https://doi.org/10.1061/(asce)em.1943-7889.0001850

Reifsnider, K., & Majumdar, P. (2013). Multiphysics stimulated simulation digital twin methods for fleet management. In *Proceedings of the 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, (pp. 1578.). American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2013-1578

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, *1*. https://doi.org/10.1017/dce.2020.16

Shen, W., Yang, C., & Gao, L. (2020). Address business crisis caused by COVID-19 with collaborative intelligent manufacturing technologies. *IET Collaborative Intelligent Manufacturing*, *2*(2), 96-99. https://doi.org/10.1049/iet-cim.2020.0041

Shirowzhan, S., Tan, W. and Sepasgozar, S.M. (2020), Digital twin and cyberGIS for improving connectivity and measuring the impact of infrastructure construction planning in smart cities, *Multidisciplinary Digital Publishing Institute*, *9*(4), 240. https://doi.org/10.3390/ijgi9040240

Simchenko, N., Tsohla, S., & Chyvatkin, P. (2019). IoT & digital twins concept integration effects on supply chain strategy: challenges. *International Journal of Supply Chain Management*, *8*(6), 803-808.

Singh, M., Fuenmayor, E., Hinchy, E. P., Qiao, Y., Murray, N., & Devine, D. (2021). Digital twin: Origin to future. *Applied System Innovation*, *4*(2), 36. https://doi.org/10.3390/asi4020036

Ibrahim, O. (2019). *Digital twin technology: A study of differences from simulation modeling and applicability in improving risk analysis*. [Master's Thesis, University of Stavanger], .http://hdl.handle.net/11250/2626223

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C.-Y., & Nee, A. Y. C. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, *57*(12), 3935–3953. https://doi.org/10.1080/00207543.2018.1443229

Tuegel, E. (2012). The airframe digital twin: some challenges to realization. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii.* (pp. 1812). https://doi.org/10.2514/6.2012-1812

Volk , R., Stengel, J., & Schultmann, F. (2014). Building information modeling (BIM) for existing buildings-Literature review and future needs. *Automation in Construction*. *38*, 109-127. https://doi.org/10.1016/j.autcon.2013.10.023

Zhao, J., Seppänen, O., Peltokorpi, A., Badihi, B., & Olivieri, H. (2019). Real-time resource tracking for analyzing value-adding time. *Automation in Construction 104*, 52-65. https://doi.org/10.1016/j.autcon.2019.04.003