AN IMPLEMENTATION STRATEGY FOR THE APPLICATION OF DIGITAL TWIN FOR CONSTRUCTION PROGRESS MONITORING USING WEARABLE TECHNOLOGIES

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Challenges such as schedule delays and discrepancies between as built and planned structures are common issues in the construction industry. Consequently, effective monitoring and analysis of construction progress remain vital aspects of productivity. Digital twins provide a promising solution to these challenges by creating a digital replica of a corresponding real-world entity, enabling simulation, tracking, analysis, and various operations throughout its entire lifecycle. Digital twins have been applied to various construction lifecycle stages to address specific issues, including BIM, structural system integrity, facilities management, monitoring, logistics processes, and energy simulation. However, a significant gap remains in utilising digital twins for construction progress monitoring with safe, wearable technologies. Employing an exploratory mixed-method approach, the study combines qualitative and quantitative analyses to recommend using digital twin applications to monitor construction progress using wearable technologies. The study proposes an implementation strategy for construction progress monitoring by integrating BIM, multiple reality capture methods (GIS, IoT, UWB, WSN), digital twin technology, and wearable technology (AR). The framework outlines methods to create, record, synthesize, interpret, and visualise construction progress analytics, information, and summaries.

Keywords: digital twin; project management; internet of things; virtual reality

INTRODUCTION

The construction industry continuously evolves and incorporates innovative technologies to improve efficiency, productivity, and overall project management (Kopsida *et al.,* 2015). One such promising technological development is the concept of Digital Twins, which has garnered significant attention in recent years. Digital Twins are digital replicas of physical assets, processes, or systems that can be used for various purposes, including performance optimisation, real-time monitoring, and predictive maintenance (Lu *et al.,* 2020). The application of Digital Twins in the

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construction industry presents an opportunity to revolutionise construction progress monitoring by utilising advanced data analysis and visualisation techniques to provide valuable insights for decision-makers.

Although the potential benefits of Digital Twins in the construction sector are widely acknowledged, there is an ongoing debate on whether a process can have a digital twin. This discussion stems from the diverse nature of construction processes, the complexity of construction projects, and the challenges associated with modelling and simulating these processes in a digital environment. While some researchers argue that Digital Twins can be effectively applied to construction processes, others claim that their implementation may be limited to specific use cases, depending on the complexity and uniqueness of the process (Duarte-Vidal *et al.,* 2021).

In this context, the integration of wearable technologies presents an exciting opportunity to enhance the application of Digital Twins for construction progress monitoring. Wearable technologies, such as smart helmets, augmented reality glasses, and sensor-equipped vests, can provide real-time data on workers' activities, movements, and locations on-site (Elghaish *et al.,* 2020). When combined with the digital representation of the construction process, this data can create a more comprehensive and accurate Digital Twin, facilitating better monitoring and decision-making. In recent years, the concept of Digital Twins has emerged as a powerful tool for optimising built asset performance and enhancing facility management practices. However, there needs to be more research in the construction industry. Most of Digital Twin's research has focused primarily on built assets and their management rather than process-based functions. This emphasis on built assets has resulted in a limited understanding of the potential benefits and challenges of implementing Digital Twins for process-oriented tasks like logistics and manufacturing (Cai *et al.,* 2017).

The construction industry is characterised by many complex processes involving multiple stakeholders, resource constraints, and various construction activities. Effective progress monitoring and control of these processes are crucial for successful project delivery (Um *et al.,* 2017). In sectors such as logistics and manufacturing, Digital Twins have been successfully employed to monitor and optimise process-based functions, leading to significant improvements in efficiency, productivity, and decision-making.

Given the proven success of Digital Twins in other industries, examining their adoption for process-based functions in the construction sector is essential. This research proposes an implementation strategy for adopting Digital Twins in construction progress monitoring using process-based functions, focusing on addressing the existing research gap in the construction industry. The objectives are: (a) to investigate the potential barriers and challenges associated with implementing Digital Twins for process-based functions in the construction industry; (b) to explore the potential opportunities Digital Twins can offer the construction industry for progress monitoring, and (c) to develop a comprehensive framework for implementing Digital Twins in construction progress monitoring.

LITERATURE REVIEW

Digital Twins (DT) refer to virtual replicas of physical entities or systems that can be used for simulation, analysis, and optimisation. A DT is established on data collected from physical entities and reflects the real-time state, working condition, or position of corresponding physical entities (Al-Ali *et al.,* 2020). Wearable technologies refer to smart electronic devices worn on the body, either as an accessory or as a part of the material used in clothing. In the construction context, these devices can be used to capture field data and automate construction project progress monitoring (Alisadehsalehi *et al.,* 2020). Process-based tasks are part of a broader process, requiring coordination and integration for successful completion. In construction, such tasks could include site planning, design, procurement, construction, and maintenance.

The digital twin market and application in industries

The global market for Digital Twins has been experiencing significant growth in recent years, with increasing demand across various industries. The Global Digital Twin market is expected to grow at a Compound Annual Growth Rate (CAGR) of 38.5% from 2020 to 2026, reaching USD 36.6 billion by 2025. According to a Technavio analysis (Technavio, 2021), the Digital Twin market is anticipated to generate USD 24.81 billion between 2021 and 2025, with a CAGR of nearly 39% throughout the projected period. This growth can be attributed to the rising digitisation in the manufacturing and production industry, prompting many businesses to reconsider their operations and strategies to remain competitive. As the demand for digital solutions grows, businesses increasingly turn to Digital Twins to overcome limitations such as connectivity costs, storage constraints, and restricted computing.

The use of Digital Twins has been documented in various industries, showcasing their versatility and applicability. Most recognised use cases are related to manufacturing (Cai *et al.,* 2017), industrial facilities (Um *et al.,* 2017), and prototype engineering (Miller *et al.,* 2018). Other applications include 5G interaction for processing plants (Cheng *et al.,* 2018), aircraft health monitoring (Li *et al.,* 2017), composite optimisation, and smart vehicles (Damjanovic-Behrendt, 2018). The fundamental premise of the Digital Twin is to create a system that connects physical entities to their digital counterparts, harnessing the advantages of both digital and physical environments for the overall system's benefit. Product data is collected, stored, and analysed, with learnings applied to current and future products.

Digital Twins improve product quality and process optimisation in the manufacturing industry by managing batch-based operations in real-time, comparing them to the "golden batch" standard. Machine learning algorithms based on factual operational model simulations built on past failure data are used to predict equipment malfunction. Digital Twins are also used during operations to evaluate real-time compliance with regulations and safety requirements for classified equipment (Qin *et al.,* 2021).

Thus, there are three key aspects to the use of Digital Twins in the manufacturing industry: (1) monitoring the status of devices, production plants, and the entire facility in real-time; (2) collecting device data to enhance the quality and performance of the manufacturing process; and (3) analysing accurate and real operational data generated by the Digital Twin to perform predictive device maintenance (Alaloul *et al.,* 2021). The widespread adoption of Digital Twins across various industries highlights their potential for enhancing efficiency, optimising processes, and reducing costs, making them an essential tool for businesses in the digital era.

Digital twin for construction progress monitoring

In construction projects, monitoring and review are crucial for identifying progress discrepancies between the as-planned and as-built status and addressing issues promptly. Time and cost overruns in construction projects can be attributed to two primary factors: efficient and accurate progress monitoring. The benefits of achieving precise tracking results using automation for construction projects include time savings, surveillance systems, cost-effectiveness, and risk monitoring of high-rise buildings. According to (Wang *et al.,* 2021), BIM has additional advantages and can provide insights and integrate with virtually any data collection and detection technology.

A ground-breaking framework introduced by Opoku *et al. (*2021) incorporates modern computer vision algorithms to enable automatic monitoring of precast walls, a critical component in precast construction. Efficient and optimal construction activity observation is vital to construction management. This framework uses object detection, instance segmentation, and multiple objects tracking to gather location and time information about precast walls from surveillance footage captured during construction (Opoku *et al.,* 2021). The obtained status data is stored in a JavaScript object notation (JSON) file, which is then used to synchronise the wall components in a corresponding BIM. The scalability, accessibility, and effectiveness of this vision-based framework are demonstrated. However, the proposed framework has three limitations: (a) Movement and viewing distance of video surveillance can impact its effectiveness due to poor lighting and camera shaking; (b) The computer vision techniques employed necessitate high-performance technology, potentially raising overall project costs, and (c) The study's primary focus is on precast wall elements, neglecting other crucial building components needed for comprehensive progress monitoring.

While BIM provides an intelligent 3D model-based process for planning, designing, constructing, and managing buildings and infrastructure, digital twins can extend this utility by offering real-time data integration, simulation, and analysis capabilities (Alisadehsalehi *et al.,* 2020). Similarly, computer vision algorithms can be beneficial for object detection and recognition, but their application can be further enhanced by integrating with digital twins for more complex tasks such as predictive analytics or real-time decision-making (Wang *et al.,* 2021).It is essential to explore innovative solutions that can address the limitations of existing construction progress monitoring technologies and expand the scope of Digital Twins to encompass various construction processes and components. By doing so, the construction industry can leverage the full potential of Digital Twins for more efficient, data-driven, and responsive project management, and this will improve cost-effectiveness, risk management, and overall project outcomes.

METHOD

This hybrid study uses an exploratory approach for data collection and combines literature review, interviews, and a questionnaire survey. This methodological design is divided into three distinct phases, each aiding in forming and validating a proposed Digital Twin framework for progress monitoring.

Phase 1: Systematic Literature Review

The first phase involves conducting a systematic literature review that spans from 2015 to 2022. Sources of secondary data include journal articles, conference papers, university research findings, government organisation reviews, company records, and industry-specific research guides. This step's objective is to analyse and summarise the current state of Digital Twin research, which forms the foundation of the framework proposed later (Krishnaswamy *et al.,* 2006).

Phase 2: Framework Development

Based on the insights derived from the literature review, a framework for utilising Digital Twins in progress monitoring is designed. This framework is shaped by the strengths, limitations, and opportunities identified in the literature concerning existing technologies and the emerging potentials of Digital Twins.

Phase 3: Experts' Evaluation of the Framework

The third phase of this research includes the evaluation of the proposed framework through expert consultations. The experts are professionals from various sectors, including site management, building operations and maintenance, facility management, and BIM. Two methods of consultation are adopted - semi-structured telephone interviews designed to foster detailed discussions and a Google Forms-based questionnaire to gather broader insights. A total of 35 professionals were contacted via LinkedIn, and 22 responses were collected after two weeks, yielding a response rate of 62.8% (Chen *et al.,* 2021).

This comprehensive methodology ensures that the proposed framework is grounded in academic literature and validated by industry professionals.

Digital Twin Framework for Progress Monitoring

This framework proposes a digital twin model for construction project monitoring that incorporates wearable IoT technology and various other elements. While the framework's scope is broader than wearable technologies, these devices are pivotal, facilitating an enhanced interactive experience and efficient communication within the construction project. The framework for digital twin implementation for progress monitoring in construction projects can be applied as follows:

(a) Ideation: At this initial stage, the core idea of integrating smart construction site sensors, IoT technologies, cloud-based BIM design models, and augmented reality (AR) into a cohesive framework for digital twin implementation in construction projects are conceived. The idea considers the potential of these technologies to revolutionise construction project monitoring by providing real-time updates, data-driven insights, and enhanced interactivity. Existing literature and technological advancements offer insights into this ideation process (Al-Ali *et al.,* 2020).

(b) Development: During the development phase, the proposed system components - smart construction site sensors, IoT data management technologies, cloud-based BIM design models, and AR glasses - are carefully selected and designed to fulfill the goal of creating an effective digital twin framework. The system architecture and operational logistics are developed, considering best practices from various studies (VanDerHorn and Mahadevan, 2021).

(c) Implementation: This stage involves the actual application and integration of the proposed system in a real-world construction project setting. Smart sensors and IoT technologies are deployed for real-time data collection, the cloud-based BIM models are uploaded and made accessible via Autodesk Forge, and the AR glasses are linked to the digital twin system to provide real-time updates and interactions. The effectiveness and efficiency of the digital twin framework are evaluated and fine-tuned during this phase.

(d) Diffusion: After successful implementation and validation, the developed digital twin framework is disseminated or diffused across the wider construction industry. This diffusion is facilitated through industry forums, seminars, publications, and collaborations. As the framework is adopted by more construction projects, the resultant data and feedback can be used to enhance the system further, thereby creating a continuous loop of improvement and innovation (Gbadamosi *et al.,* 2021).

The proposed framework is designed to provide a comprehensive solution for progress monitoring in construction projects by integrating advanced technologies for data collection, processing, analysis, and visualisation. By leveraging wearable IoT devices and augmented reality, the framework aims to enhance decision-making, facilitate collaboration, and reduce construction errors on site. The proposed framework offers numerous benefits and opportunities for managing construction sites, automation, enhanced performance, safety, and tracking of activities and workers: (a) Improved Decision-Making: Real-time data collection and analytics enable stakeholders to make informed decisions based on accurate and up-to-date information, leading to better planning, scheduling, and resource allocation; (b) Enhanced Performance Monitoring: By continuously tracking construction progress and comparing it to the digital twin, discrepancies and deviations can be detected early, allowing for prompt corrective actions and improved overall performance; (c) Increased Automation: The framework supports integrating innovative construction technologies, such as automated cranes and robotic equipment, reducing reliance on manual labour and increasing efficiency; (d) Improved Safety: Continuous monitoring of construction site conditions, equipment usage, and worker activities helps identify potential safety hazards and address them proactively. This can reduce accidents, protect workers, and minimise project delays due to safety incidents; (e) Real-time Activity and Worker Tracking: By employing IoT and wearable technologies, the framework allows for seamless tracking of workers and activities on-site, leading to better coordination, task allocation, and productivity; (f) Enhanced Collaboration: The cloud-based BIM collaborative environment facilitates real-time information sharing and coordination among various stakeholders, such as architects, engineers, and construction managers, resulting in better collaboration and streamlined workflows; (g) Cost and Time Savings: By identifying potential issues early, minimising errors, and improving overall efficiency, the framework can lead to high cost and time savings throughout the construction process.

Despite the numerous benefits of the proposed framework, several barriers must be addressed to ensure successful implementation: (a) Connectivity: Reliable and high-speed connectivity is essential for real-time data transfer and communication between various components in the framework. Construction sites may face challenges in establishing consistent and robust connectivity, especially in remote or densely built areas; (b)3D Model Requirement: Creating and maintaining accurate and up-to-date 3D models for digital twins can be time-consuming and resource intensive. This may pose a challenge for smaller projects or organisations with limited resources; (c) Data Security: As the framework relies on cloud-based data storage and communication, ensuring data security and privacy becomes crucial. There is a risk of unauthorised access or data breaches, which can have severe implications for project stakeholders; (d) Holistic Transformation of Digital Infrastructure: The adoption of the framework requires a complete transformation of the existing digital infrastructure, which can be a significant challenge for organisations with traditional construction methods and systems. The transition may be resource-intensive and require extensive planning and coordination; (e) Hardware Requirements: Implementing the framework may necessitate significant investments in hardware, such as sensors, wearable devices, and other IoT components. This can be a financial barrier for smaller organisations or projects with tight budgets; (f) Expertise: The successful implementation and management of the framework require a skilled workforce with expertise in various technologies, such as IoT, BIM, data analytics, and AI. There may be a need for more qualified professionals in the industry, or additional training may be required for the existing workforce, and (g) AI Ethics: The use of AI and machine learning within the framework raises ethical concerns, such as algorithmic bias and transparency in decision-making processes. Ensuring ethical AI practices and addressing potential biases in the algorithms are essential to avoid unintended consequences and maintain trust among stakeholders.

Experts' Evaluation

The key advantages and disadvantages of implementing digital twin technology in the construction sector were identified in previous literature. To gain further insights from industry professionals, a questionnaire survey was conducted with 22 participants, all providing valid responses. This sample size was deemed suitable for balancing time constraints and the need for reliable data. Participants' construction experience varied from one to over ten years, and their roles included Facility/Project Manager, BIM Specialist, Civil Engineer, Architectural Design Consultant, and Research Engineer, among others.

Of the 22 participants, 40.9% (9 individuals) demonstrated a level 3 familiarity with digital twins. Most respondents believed that digital twin technology could benefit the construction industry by enhancing work management efficiency, automating progress monitoring, improving performance, simulating scenarios, and ensuring safety. These factors received a 59% approval rating. In comparison, the remaining 41% of participants agreed that digital twins could assist in real-time data management, reducing operational and construction costs and optimising asset performance.

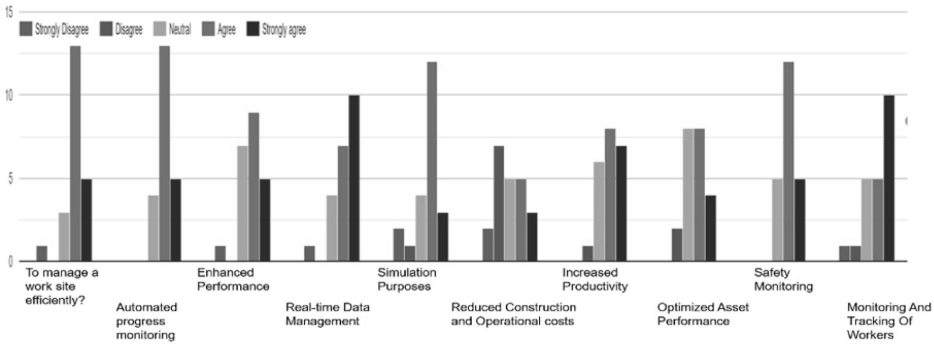

Figure 1: Opportunities of Using Digital Twin for Progress Monitoring

Only one participant disagreed that digital twins could help with simulations, increased productivity and collaboration, and worker monitoring and tracking. Regarding optimal asset performance and sustainability, 36.36% of respondents remained neutral, and 31.81% stayed neutral for improved operational performance, as depicted in Figure 2.

Participants acknowledged the drawbacks of employing digital twin technology in the construction industry. Ethical concerns were identified as a significant disadvantage, with 45% of participants strongly agreeing on this issue, as shown in Figure 3.

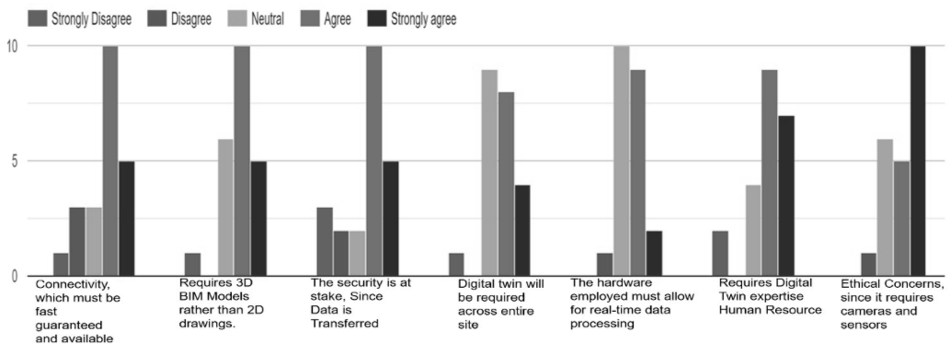

Figure 2: Barriers for Digital Twin Implementation

An expert validation was also conducted with interviewees familiar with the Digital Twin framework and who had experience in IoT-based construction projects, providing valuable insights into the framework's potential impact on construction site management. They emphasized the importance of reliable data collection, using advanced sensors like optical fibre detectors for real-time monitoring. They also highlighted the benefits of AR training for improved site management and worker response. The interviewees noted that implementing the Digital Twin framework could lead to significant cost savings and better synchronisation of design models across disciplines using Autodesk Forge API and the Forge platform. Additionally, they mentioned that supply chain segmentation based on construction stages is crucial for effective planning and execution.

CONCLUSIONS

This study developed a Digital Twin framework to enhance construction progress monitoring by incorporating wearable Augmented Reality (AR) technology. The framework combined various technologies to address the construction site tracking challenges faced by the AEC industry. By offering continuous access to real-time as-planned and as-built model simulations, the Digital Twin architecture allows decision-makers to monitor project status effectively.

The framework integrates BIM, GIS, UWB, WSN, and AR technologies, translating complex information into an intuitive AR visualisation platform for improved monitoring and decision-making. Advanced analytic technologies like AI and ML enable better prediction and response to potential challenges.

The framework streamlines and improves time-consuming management activities by efficiently acquiring data, virtualising construction activities, updating project documentation instantly, displaying information on a relative scale, and redistributing findings and operations to the cloud. Based on the input from industry professionals, the validation process demonstrated that the framework benefits management, interoperability, remote judgment, automation, and collaborative effectiveness.

In conclusion, this study explored and promoted using Digital Twin applications in combination with AR glasses to collect data and monitor construction site progress. The framework, integrating BIM, multiple reality capture methods, Digital Twin, and wearable AR technology, offers a comprehensive approach to creating, recording, synthesising, interpreting, managing, and visualising construction progress analytics and information. Using a quantitative questionnaire survey, the advantages, and disadvantages of using digital twins in the construction industry were also examined.

The Digital Twin framework is crucial in project management, simulation, analysis, and alignment with organisational goals and requirements.

REFERENCES

Al-Ali, A.R, Gupta, R, Zaman Batool, T, Landolsi, T, Aloul, F and Al Nabulsi, A (2020) Digital twin conceptual model within the context of internet of things, *Future Internet*, **12**(10), 163.

Alaloul, W S, Qureshi, A H, Musarat, M A and Saad, S (2021) Evolution of close-range detection and data acquisition technologies towards automation in construction progress monitoring, *Journal of Building Engineering*, **43**, 102877.

Alisadehsalehi, S, Hadavi, A and Huang, J C (2020) From BIM to extended reality in AEC industry, *Automation in Construction*, **116**, 103254.

Cai, Y, Starly, B, Cohen, P and Lee, Y S, 2017 Sensor data and information fusion to construct digital-twins virtual machine tools for cyber-physical manufacturing, *Procedia Manufacturing*, **10**, 1031-1042.

Chen, L, Xie, X, Lu, Q, Parlikad, A K, Pitt, M and Yang, J, 2021 Gemini principles-based digital twin maturity model for asset management, *Sustainability*, **13**(15), 8224.

Cheng, J, Chen, W, Tao, F and Lin, C L (2018) Industrial IoT in 5G environment towards smart manufacturing, *Journal of Industrial Information Integration*, **10**, 10-19.

Damjanovic-Behrendt, V (2018) September A digital twin-based privacy enhancement mechanism for the automotive industry, *In*: *2018 International Conference on Intelligent Systems (IS)*, IEEE, 272-279

Duarte-Vidal, L, Herrera, R F, Atencio, E and Muñoz-La Rivera, F (2021) Interoperability of digital tools for the monitoring and control of construction projects, *Applied Sciences*, **11**(21), 10370.

Elghaish, F, Matarneh, S, Talebi, S, Kagioglou, M, Hosseini, M.R and Abrishami, S (2020) Toward digitalisation in the construction industry with immersive and drone technologies: A critical literature review, *Smart and Sustainable Built Environment*, **10**(3), 345-363

Gbadamosi, A Q, Oyedele, L O, Delgado, J M D, Kusimo, H, Akanbi, L, Olawale, O and Muhammed-Yakubu, N (2021) IoT for predictive assets monitoring and maintenance: An implementation strategy for the UK rail industry, *Automation in Construction*, **122**, 103486.

Kopsida, M, Brilakis, I and Vela, A (2015) A review of automated construction progress monitoring and inspection methods, *In*: *Proceeding of the 32nd CIB W78 Conference*, 421-431).

Krishnaswamy, K N, Sivakumar, A.I and Mathirajan, M (2006) *Management Research Methodology: Integration of Principles, Methods and Techniques*, Pallavaram, Chennai, India: Pearson Education India.

Li, C, Mahadevan, S, Ling, Y, Choze, S and Wang, L (2017) Dynamic Bayesian network for aircraft wing health monitoring digital twin, *Aiaa Journal*, **55**(3), 930-941.

Lu, Q, Parlikad, A K, Woodall, P, Ranasinghe, G D, Xie, X, Liang, Z, Konstantinou, E, Heaton, J and Schooling, J (2020) Developing a digital twin at building and city levels: A case study of West Cambridge campus, *Journal of Management in Engineering-ASCE*, **36**(3).

Miller, A.M, Alvarez, R and Hartman, N (2018) Towards an extended model-based definition for the digital twin, *Computer-Aided Design and Applications*, **15**(6), 880-891.

Opoku, D.G.J, Perera, S, Osei-Kyei, R and Rashidi, M (2021) Digital twin application in the construction industry: A literature review, *Journal of Building Engineering*, **40**, 102726.

Qin, H, Wang, H, Zhang, Y and Lin, L (2021) Constructing digital twin for smart manufacturing, *In*: *2021 IEEE 24th International Conference on Computer Supported Cooperative Work in Design (CSCWD)*, IEEE, 638-642.

Um, J, Weyer, S and Quint, F (2017) Plug-and-simulate within modular assembly line enabled by digital twins and the use of automationML, *IFAC-Papersonline*, **50**(1), 15904-15909.

VanDerHorn, E and Mahadevan, S (2021) Digital Twin: Generalisation, characterisation and implementation, *Decision Support Systems*, **145**, 113524.

Wang, Z, Zhang, Q, Yang, B, Wu, T, Lei, K, Zhang, B and Fang, T (2021) Vision-based framework for automatic progress monitoring of precast walls by using surveillance videos during the construction phase, *Journal of Computing in Civil Engineering*, **35**(1), 04020056