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Research Article

IoT-Enabled Digital Twin for Autonomous Modular Construction Progress Monitoring

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Abstract

This study aims to develop and validate an autonomous progress monitoring solution for modular construction using DT technology. The goal is to address limitations in current modular construction monitoring by integrating IoT technologies with DT platforms to provide real-time, actionable insights and enhance project coordination. A DSR methodology was adopted to guide systematic development and validation of the proposed DT-based artefact. The research involved a detailed literature review to identify existing gaps in modular construction progress monitoring, followed by design, implementation, and testing of a practical DT solution using a simulated modular construction case study. The solution integrates close-range IoT technologies—specifically RFID tags and readers—to capture pre-defined element status data and generate real-time progress visualisation. The findings confirm that DTs, when coupled with appropriate IoT technologies, can provide a feasible and scalable solution for autonomous progress monitoring in modular construction. Close-range tracking technologies were found to offer the most reliable and accessible means for data collection. The solution emphasises simplicity and practicality, using minimal but targeted data to deliver meaningful progress metrics. The novel DT ontology further supports adaptability across diverse project settings, ensuring broader applicability. This research makes a novel contribution by presenting a validated, lightweight DT-based progress monitoring framework tailored to the unique characteristics of modular construction. Unlike traditional 4D BIM approaches, the solution prioritises automation, accessibility, and operational efficiency, aligning with Industry 4.0 objectives. It offers a replicable architecture for future DT implementations in construction, thereby advancing both academic understanding and industrial practice.

Keywords: Digital Twins; 4D BIM; Instantaneous Progress Monitoring; DT ontology; DSR; IoT

Highlights

- Validated a lightweight DT framework for autonomous progress tracking in modular construction.
- Integrated RFID-based IoT with DTs to enable real-time, accessible, and scalable data collection.
- Demonstration of potential for improved project coordination though minimal, targeted progress visualisation metrics.

1 Introduction

Driven by Industry 4.0 technological advances, the built environment is undergoing significant transformation (Elghaish et al., 2022; National Building Specification, 2021; RICS, 2023; Zambrano et al., 2022). As construction projects grow in size and complexity, progress monitoring solutions deliver efficiency gains while also introducing automation requirements of the monitoring processes (Kim, Kim, & Son, 2013). As automation is achieved through the digitalisation of processes, data mining is expected to play an important role in real-time site monitoring. The collected information can be used to create simulations to improve 4D building information modelling (BIM), simulation methods, and forecasting (Nguyen, Moon, & Ahn, 2022). Additional efficiency gains are offered by modular methods of construction when compared to traditional methods of construction, with prefabricated buildings also predicted to achieve greater life-cycle performance (Kamali & Hewage, 2016). The main barriers of modular construction, or Modular Integrated Construction (MiC), are identified as: road network capability/capacity, transportation, attaining design freeze, site access, and on-site storage (Tsz Wai et al., 2021). Effective project planning and management is required to address the challenges of MiC, with cooperation among stakeholders presenting a key area to address (Dong et al., 2022). Just-in-time (JIT) production philosophies are suggested to mitigate the issues of storage and handling of elements on and off site (Hussein & Zayed, 2021). JIT for MiC requires effective progress monitoring.

Digital Twins (DTs) are becoming increasingly popular in all sectors of industry, providing value by representing physical systems in digital domains with real-time feedback and control (Huang, Shen, Li, Fey, & Brecher, 2021; Sharma, Kosasih, Zhang, Brintrup, & Calinescu, 2022). The majority of built environment DTs relate to the operational phase of assets, or city-wide monitoring and control of systems such as power or transport (British Standards Institution, 2017; Fuller, Fan, Day, & Barlow, 2020; Kaewunruen, Rungskunroch, & Welsh, 2019). Research on DT applications for progress monitoring has focused on on-site contexts (Alizadehsalehi & Yitmen, 2023a), with MiC methods receiving limited attention (Jiang, Li, Guo, et al., 2022). Despite substantial potential benefits, modular construction DT research remains limited and faces numerous challenges (Aldabbas, 2023). The successes achieved through DT integration in manufacturing processes (Fuller et al., 2020; Rasheed, San, & Kvamsdal, 2020) warrant investigation into DT applications in modular construction projects, particularly given that modular elements are fabricated in manufacturing facilities and follow repetitive sequential life-cycles. This research develops and validates a novel autonomous DT-based progress monitoring solution for modular construction projects.

2 Conceptual Background

2.1 Progress Monitoring

Currently, traditional progress monitoring, whereby a site supervisor manually inspects the progress of a project and enters the status into a scheduling system, is most commonly used (Hannan Qureshi et al., 2022). Current research is aimed at integrating emerging digital technologies with construction processes to achieve greater efficiency; close-range digital technologies such as RFID and laser scanners are the prominent methods for autonomous progress monitoring (Hannan Qureshi et al., 2022). Early research has highlighted the value of integrating schedule with design information, with researchers such as Cheng and Chang (Cheng & Chang, 2001) developing custom applications to receive data from RFID and barcodes to track key materials status. More recently vision-based status monitoring has gained popularity (Kavaliauskas, Fernandez, McGuinness, & Jurelionis, 2022; Sami Ur Rehman, Shafiq, & Ullah, 2022; Wang et al., 2021) but faces challenges relating to a lack of connectivity with construction applications (Sami Ur Rehman et al., 2022), element recognition (Kavaliauskas et al., 2022; Wang et al., 2021), and effort required to make image information usable (Kavaliauskas et al., 2022). The following table summarises recent modular progress monitoring solutions.

Table 1: Existing research on progress monitoring solutions.

Item	Focus of Study	Method/Contribution
Wang, Z. et al. (2021)	Image based progress monitoring of precast, linking to Revit to update time and location metadata based on element status.	Generation and assessment of a vision-based Framework.
Zhou, J.X. et al. (2021)	Smart BIM platform for progress monitoring of MiC projects utilising wearable IoT to scan physical elements, sending status information to scheduling application.	Case study of real-world project with development and evaluation of a working platform – Design Science Research.
Cheng, M.-Y. & Chang, G.-L. (2001)	Utilises bar code and RFID to transmit status information to a scheduling application	Development of a working solution - Design Science Research.
Kavaliauskas, P. et al. (2022)	Utilises point cloud scanners to generate as built model which overlays an IFC BIM model, comparing elements percentage completion.	Development and evaluation of a working solution - Design Science Research.
Alizadehsalehi, S. & Yitmen I. (2023)	A Framework for automated progress monitoring integrating BIM with multiple reality capturing technologies, presented using extended reality systems.	Generation and assessment of a BIM integrated reality capture Framework.
Jiang, Y. et al. (2022)	An on-site, storage to quality control, Framework for modular progress monitoring utilising RFID and wearable technologies to update DT status	Generation of a Framework leading to development of a working solution – Design Science Research

[1] A summary of progress monitoring solutions

2.2 Digital Twins (DTs)

The DT concept is a continually synchronising autonomous virtual representation of a physical system, enabled by technologies such as the Internet of Things (IoT) that grant instantaneous data collection from the physical twin, which over time can be used to generate simulations of future scenarios (Fuller et al., 2020; Rasheed et al., 2020). The concept originated in manufacturing and aerospace applications, with NASA utilising the first practical application of the 'twin' concept during the Apollo space program, mimicking the craft in space to a twin on Earth (Liu, Fang, Dong, & Xu, 2021; Rasheed et al., 2020). The principal benefits of a DT lie in its capacity to process data for the identification of inefficiencies and emerging issues, thereby enabling robust management across the entire life-cycle of complex systems (Fuller et al., 2020; Liu et al., 2021; Rasheed et al., 2020). These capabilities distinguish the DT concept as superior to 4D BIM processes.

The current digitalisation of the built environment driven by Industry 4.0 is facilitating the adoption of DTs to the built environment value chain (Boje, Guerriero, Kubicki, & Rezgui, 2020; Fuller et al., 2020; HM Treasury, 2015; Rasheed et al., 2020). Research suggests that DTs can integrate with modular construction projects to improve project coordination, bringing the benefits of DTs to the construction phase (Aldabbas, 2023; Jiang, Li, Guo, et al., 2022; Jiang, Li, Li, et al., 2022). Challenges to incorporating DT concepts to modular construction must be considered, most of which are related to the complexity of the systems and the knowledge gap that exists within industry (Aldabbas, 2023). These challenges are faced by DTs generally and include the large amount of data DTs generate that requires collection, sorting, analysis, and storage (Rasheed et al., 2020). Thus, data quality is central to the successful implementation of DTs (Fuller et al., 2020), raising the issue of data security, relevant to sensitive systems that are vulnerable to cyber-attacks (Baig et al., 2017; Fuller et al., 2020; Rasheed et al., 2020).

Due to the prefabrication of modular elements, manufacturing DTs can be applied to production processes to offer efficiency benefits, while also providing the foundation for DT concepts to be utilised in later project stages (Aldabbas, 2023). In relation to precast concrete elements, von Danwitz et al. (von Danwitz et al., 2023) applied DT concepts to assess the structural integrity of a reinforced concrete beam. The domain of DTs relies heavily on advancements of emerging digital technologies such as sensors, artificial intelligence (AI), and data analytics (Akanmu, Anumba, & Ogunseiju, 2021; Aldabbas, 2023; Fuller et al., 2020). Technological obsolescence is a concern when using such technologies, raising the need for mitigation by providing retrofittable sensors (Fuller et al., 2020), backwards compatibility of all systems (Rasheed et al., 2020), provision of 5G and onward infrastructure for network capacity (Huang et al., 2021), and building trust and knowledge in the fields of AI and machine learning (Fuller et al., 2020).

2.3 Internet of Things (IoT)

The popularity of IoT technologies has grown across all sectors in recent years, enabled by improved network connectivity, the development of AI technologies, the digitisation of processes, and cost-effective sensors (Rasheed et al., 2020). In essence the term refers to a collection of devices connected to a network that are capable of collecting and relaying information, allowing for remote real-time monitoring of systems (Fuller et al., 2020), thus making IoT devices ideal for acquiring the physical systems data for DTs. There are multiple suppliers providing IoT platforms in today's market, such as Amazon web services, Microsoft Azure, Salesfore IoT, and Oracle IoT (Radanliev et al., 2022; Rasheed et al., 2020). Utilization of such services mitigates the challenges of costly data processing and management (Liu et al., 2021) for enterprises aiming to incorporate IoT technologies. The integration of IoT technologies as data receptors of complex and intelligent systems is driving Industry 4.0 (Oztemel & Gursev, 2020) and are a core enabler of DTs (Fuller et al., 2020).

As IoT refers to devices and not a singular solution there is flexibility in how the data can be collected, allowing for adaptability to individual cases (Liu et al., 2021). The type of data required to feed the DT will influence the device used to collect the data; poor device selection may lead to a weak link in the channelling of information (Foroughi Sabzevar, Gheisari, & Lo, 2023). In relation to modular construction, Radio Frequency Identification (RFID) tags and readers have proven beneficial for manufacturing and supply chain management, as well as enabling the first-generation cyber physical systems (Oztemel & Gursev, 2020). The read/write capability of RFID tags allow for accurate scheduling and tracking information in a manufacturing scenario (Kokuryo, Kaihara, Suginouchi, & Kuik, 2016), as well as logistical benefits achieved through the quick and accessible data collection RFID tags support (Oztemel & Gursev, 2020). In relation to BIM, RFID tags are often mentioned in studies relating to site monitoring and 4D BIM processes (Boje et al., 2020). Another study has highlighted how Quick Response (QR) codes can be used to provide a channel-link from a printed master drawing to a digital detail drawing, integrating the physical and digital domains of BIM (Foroughi Sabzevar et al., 2023).

2.4 Existing Progress Monitoring DTs Theories and Frameworks

The nature of DTs presents effective progress monitoring, with value coming from automated instantaneous updates. A common focus of studies relating to construction progress monitoring utilising DTs are focused on cast-in-situ construction (Jiang, Li, Guo, et al., 2022). With the benefits DTs offer to manufacturing processes (Rasheed et al., 2020) the potential benefits of a modular construction DT could be twofold. The development of a DT for construction progress monitoring frequently involves the integration of BIM data or models (Alizadehsalehi & Yitmen, 2023a; Jiang, Li, Guo, et al., 2022; Lu, Xie, Parlikad, & Schooling, 2020), which often requires a highly developed BIM of the project which may not be available at the time a modular construction enterprise would want to develop a progress monitoring DT. Considering that it is only during the late pre-construction and construction phase that the multiple project parties begin to combine their fragmented models (Boje et al., 2020), it becomes unlikely a sufficiently developed project BIM model would be available for an enterprise to reap the benefits of a progress monitoring DT for modular construction. The table below presents some examples of progress monitoring DTs, highlighting the method and limitations of such studies.

Due to the changing geometry and evolving site conditions that occurs as a structure is constructed, on-site sensor positioning needs frequent adjustment and must assess exact geometry changes, it is this reason that the majority of solutions adopt a visual-based technology (Reja, Varghese, & Ha, 2022). With modular construction, exact geometry measurements are unnecessary, as the exact geometry of the prefabricated element is known and also often exists in a virtual model (Jiang, Li, Guo, et al., 2022). Practical investigation of solutions is often mentioned as suggestions for further research in progress monitoring DT related papers, with the infancy of emerging technology being a common limit of such research.

Table 2: Progress monitoring digital twins.

Item	Focus of Study	Method/Contribution	Limitations/Future Research
Alizadehsalehi et al. (2023) (Alizadehsalehi and Yitmen, 2023b)	Vision-based DT framework for automated progress monitoring management	Integration of reality capture technologies with DT concepts to enhance progress monitoring	Practical application and assessment of framework required to further validate framework
Jiang et al. (2022) (Jiang, Li, Guo, et al., 2022)	Modular integrated construction DT with focus mitigating the uncertainty of the assembly stage	A DT smart MiC system to measure assembly status and site resources using smart devices for data collection	To fully utilise this DTs potential, particularly the predictive and automated capabilities, a robust self-sufficient and self-learning AI is required
Pal et al. (2023) (Pal et al., 2023)	DT construction to enable automation of progress monitoring	A framework for linking DT construction concepts with automated construction project management	Practical application and assessment of framework required to further validate framework
Si et al. (2023) (Si et al., 2023)	Extraction of meaningful data from the design and construction phase to improve progress monitoring using DT concepts	A framework for a self-organising data mining system to enhance reliability of construction progress monitoring DTs	Practical application and assessment of framework required to further validate framework
Kosse et al. (2024) (Kosse et al., 2024)	Improvement of on-site coordination using Industry 4.0 technologies	A tracking system that combines camera-based data collection with DT concepts to improve progress monitoring	Practical application and assessment of framework required to further validate framework

[2] A summary of progress monitoring digital twins

2.5 Knowledge Gaps and Research Opportunities

The challenges of implementing progress monitoring DTs are presented in the table below, along with perceived severity, and possible solutions. Notable issues are those relating to standardisation and the development of closed systems, which impede collaboration and scalability. Rapid technological change complicates futureproofing, while expanding twins across projects increase data processing demands. Though solutions like standardised architectures and reduced data ingestion rates exist, most remain untested in complex environments. Relying on supplier platforms may aid compatibility but risks long-term adaptability. This research proposes a simplified, practical DT solution targeting essential data capture and efficient integration to meet industry needs.

Table 3: The challenges in progress monitoring digital twin implementation.

Author/Year	Challenge	Focus of Study	Severity	Possible Solutions
(Kim, Kim and Son, 2013; Wang et al., 2021; Hannan Qureshi et al., 2022; Kavaliauskas et al., 2022; Reja, Varghese and Ha, 2022; Pal et al., 2023)	Integration of Visual-Based Technologies	Perceived workload to implement visual-based data collection is increased versus non-visual devices.	Low	Utilise non-visual devices for data collection. Create a Framework to improve efficiency of visual devices
(Eriksson FRICS et al., 2017; Boje et al., 2020; Fuller et al., 2020; Rasheed, San and Kvamsdal, 2020; Huang et al., 2021; Jiang, Li, Li, et al., 2022; Aldabbas, 2023)	Closed Systems and Standardisation	End solution outcome could be a closed system with little standardisation, resulting in little prospect for collaboration or widespread adoption.	High	Use standardised systems for solution development and follow BIM collaboration principles. Create a customisable solution.
(Huang et al., 2021; Liu et al., 2021)	Reliance on a fully developed BIM model or project information	Solution may be excessively integrated with BIM principles, creating a dependency on high-quality models or information.	Moderate	Focus on using the modular element model for virtual representation. Focus on the collaborative aspect of BIM by making the twin accessible and easy to understand.
(Liu et al., 2021; Jiang, Li, Li, et al., 2022; Nabeeh et al., 2022; Alizadehsalehi and Yitmen, 2023b)	Reliance on Immature Technologies	Although emerging technologies offer great benefits building the twin around technologies in their early stages limits its practicality.	Low	Utilise technologies that are accessible and do not require in-depth understanding to implement. Utilise commonly adopted technologies where possible
(Eriksson FRICS et al., 2017; Boje et al., 2020; Fuller et al., 2020; Alizadehsalehi and Yitmen, 2023b; Si et al., 2023)	Data Collection and Management	Large data ingestion will be costly and more complex, decreasing the accessibility of the solution.	Moderate	Build the solution to run on as little data as possible. Limit the frequency of sending data to essential events.
(Fuller et al., 2020; Rasheed, San and Kvamsdal, 2020; Liu et al., 2021)	Compatibility and Network	Forward and backward compatibility must be considered for future proofing, as well as emerging networks like 6G.	High	Remove this from the scope of the solution and utilise a supplier's platform. Use up to date devices and technology.
(Chourabi et al., 2012; British Standards Institution, 2015; Fuller et al., 2020; Rasheed, San and Kvamsdal, 2020)	Security and Privacy	Ensuring security and privacy will be more important to some projects than others.	Moderate	Limit the amount of information held on the twin, decrease the potential power an attacker could hold. Rely on third party security solutions.
(Fuller et al., 2020; Liu et al., 2021; Nabeeh et al., 2022)	Integration of IoT Technologies	Poor selection of IoT devices may lead to decreased accuracy and efficiency of the twin.	High	Choose technologies that are known to work with twins. Keep devices simple.
(Chourabi et al., 2012; Aldabbas, 2023)	Lack of Knowledge and Expertise	There is a knowledge gap in industry relating to the subject matter.	Moderate	Keep solution as simple as possible. Use industry standards where possible.

[3] A summary of the challenges facing progress monitoring digital twin implementation

2.6 Proposed Conceptual Model

Although there is no clear definition for DT, the concept is generally understood to be an accurate, instantaneous, synchronous, virtual representation of a physical system or sub-system (Liu et al., 2021). Integration of IoT technologies have also become a core aspect of the cyber-physical connection (Fuller et al., 2020; Rasheed et al., 2020). Developing a practical DT requires a clear understanding of the required value-adding information of modular construction progress monitoring. Considering the challenges of over-complexity and non-customisable solutions found in the literature review this solution aims to provide essential status updates, (e.g. 'produced', 'delivered' 'installed'). The system comprises three layers: IoT for data collection and cloud storage, a 3D model for virtual project representation, and a data integration layer that merges both to visualise progress. To address compatibility and network issues, Microsoft Azure was used as the third-party platform to develop this infrastructure. Microsoft Azure provides a holistic platform for DT development that allows in-depth customisation of systems to tailor solutions to end users' requirements (VanDerHorn & Mahadevan, 2021). The architecture of this solution as discussed is represented in the figure below.

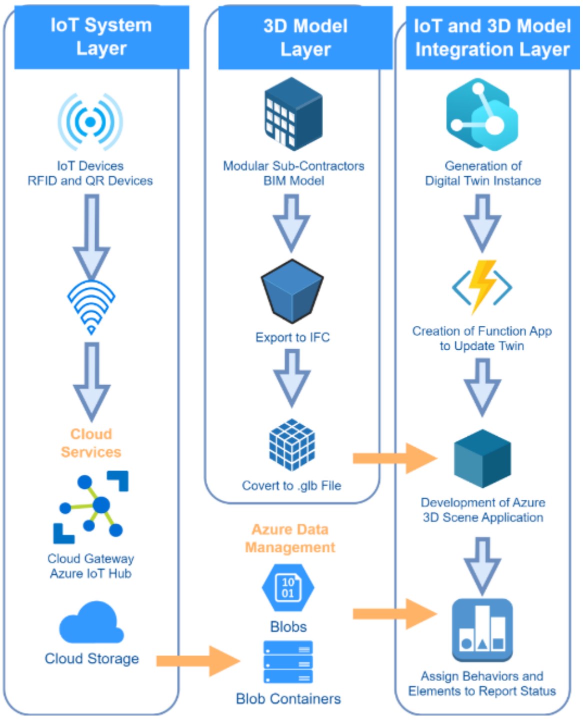

Figure 1: Digital twin architecture for modular construction progress monitoring.

An ontology provides a structure for how the information will be organised and represented within the DT; it is the mechanism that enables the twin to function. There are many sample or template ontologies to choose from, however none suited the case of modular construction progress monitoring with most aimed towards manufacturing or facility management. Due to this, a novel ontology was created to suit modular construction requirements and face the challenges identified. At the top of the ontology is the project interface, comprising element and production data. It links directly to the element interface via a 'Has Element' relationship. The production facility also links to the element interface through 'Element Data' for sequencing and planning, which informs pre-production status. The element interface connects to devices that collect an element's life-cycle data. One device, associated through 'Has QR', links the QR code on the production drawing. This captures events like drawing receipt and production stage status. Three additional devices use RFID tags. The production team scans a tag to mark the element as produced. A trailer scan shows loading, and a crane scan indicates installation once the tag exits range. The trailer also scans gate tags to confirm yard exit and site delivery. The setup aims for simplicity while ensuring accurate status tracking, adopting a lean approach to data acquisition. The final ontology is presented in the figure below.

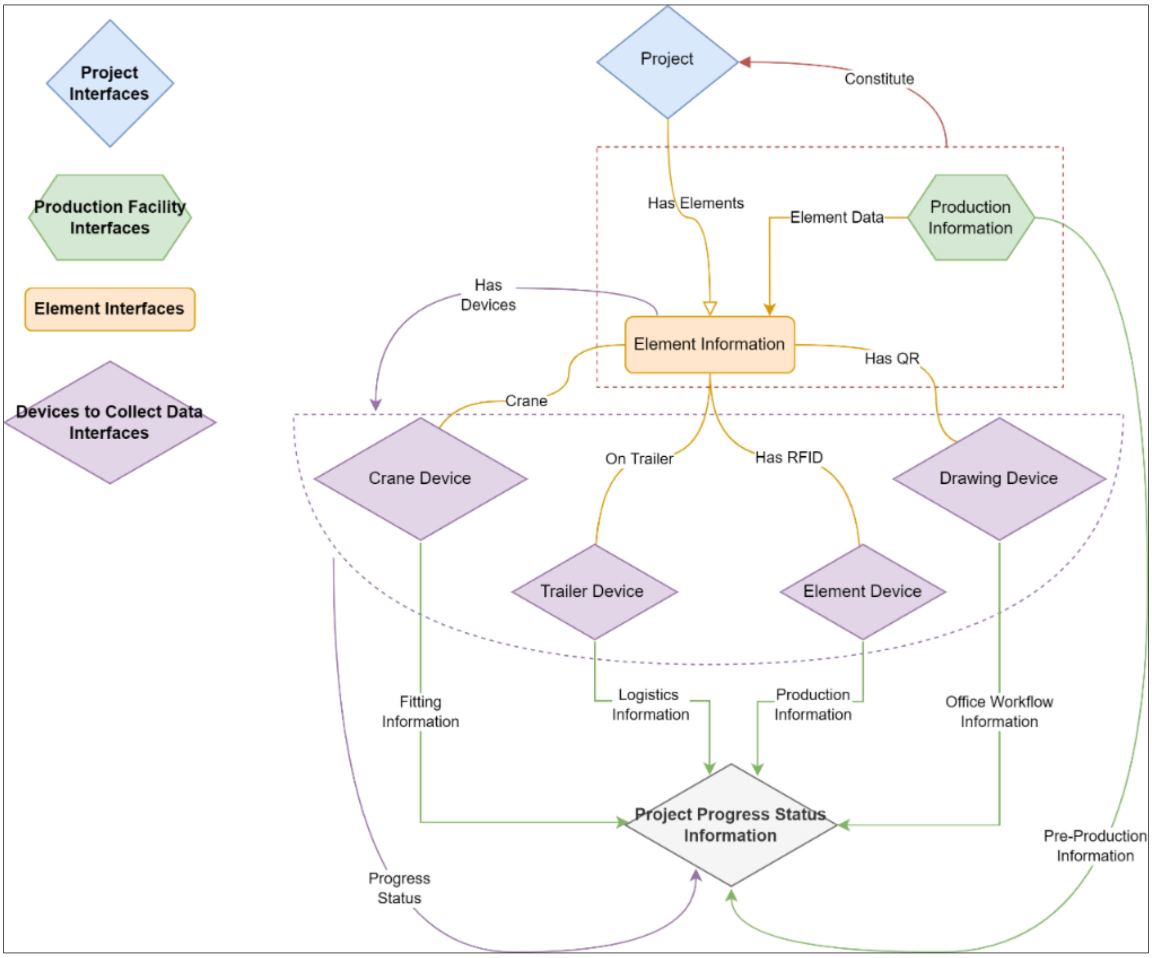

Figure 2: Novel modular construction progress monitoring ontology.

3 Methodology

The core aim of this research is the development of a practical working solution rather than the advancement of theory alone, making traditional empirical methods unsuitable. A Design Science Research (DSR) paradigm addresses defined problems through the creation of innovative Information and Communication Technology (ICT) artefacts (Muntean, Danaiata, & Hurbean, 2021), making it an appropriate choice for this study. DSR provides a structured approach for exploring and developing solutions within complex systems that have limited theoretical foundations and consist of multiple interdependent components (Vaishnavi & Kuechler, 2015). DSR follows a particular schema comprising: Identification of the goals of the artefact; The specific approach employed; A clear description of the artefact; Evaluation; Discussion, and Conclusions (McGibbon & Van Belle, 2015).

In the problem identification phase, a literature review was conducted to investigate existing solutions, frameworks, and key areas relating to the topic. During objective definition, insights from the review were used to develop specific goals for the artefact. In the design and development phase, the artefact was implemented using Microsoft Azure, and the DT interfaces were created with the Digital Twin Definition Language (DTDL). Project data were then simulated, ingested through Azure Functions, stored on the twin, and visualised on the Azure 3D scene studio. The evaluation phase involved applying the artefact within a simulated case study to test its functionality and integration. During evaluation, the artefact's performance and practicality in addressing the defined problem were assessed, identifying areas for improvement. Finally, in the discussion and conclusions phase, the artefact's viability and findings were documented and discussed. This structured approach ensured that data analysis focused on the artefact's real-world applicability and its ability to address the identified challenges (Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007; Vaishnavi & Kuechler, 2015).

4 Results – Key Findings

To conduct the evaluation of the artefact a mock project was created of a precast sports stadium stand, with fictitious progress data used to feed the Twin. To test the full extent of the artefact it was decided that the simulation would include elements at each project state. To mimic a project that was underway, the first seating terrace bay was simulated as being fitted by preloading data into interfaces. The speed of the simulated device updates was also increased to create a practical demonstration of project progression, element tracking on a project like this would continue for weeks or months. Focus was placed on the artefact's ability to address the challenges identified in the literature review.

The security and privacy of Microsoft Azure is not in the control of the researcher or any other user of the platform and, therefore, cannot be improved. To improve security and privacy a novel closed system would have to be developed which goes against the architecture and accessibility principles of the presented solution. Another consideration is the complexity of the solution. Steps were made to reduce the complexity of the system, however there is no apparent benefit from simplifying the solution further. Overall, the objective to test the proposed platform for effectiveness, identifying deficiencies and areas for improvement was achieved through the evaluation of the artefact using simulation. The evaluation case study proved effective at providing an assessment of the proposed solution. The presented artefact was found to be an effective progress monitoring solution for modular construction, with no concrete data being presented by the case study which required improvement or adjustment. Comparing the results of the evaluation to the challenges identified earlier provides an assessment of artefact. The table below presents the evaluation of whether the challenges were mitigated, and the perceived severity of the challenge.

Table 4: Evaluation of solution.

Challenge	Severity	Result
Integration of Visual-Based Technologies	Low	Mitigated by using non-visual devices
Closed Systems and Standardisation	High	Mitigated
Reliance on a fully developed BIM model or project information	Moderate	Mitigated
Reliance on Immature Technologies	Low	Mitigated
Data Collection and Management	High	Mitigated
Compatibility and Network	High	Mitigated
Security and Privacy	Moderate	Uncertain
Integration of IoT Technologies	High	Mitigated
Lack of Knowledge and Expertise	Moderate	Mitigated

[4] A summary of artefact evaluation

Not all identified challenges have been mitigated by this solution. However, the challenges with a high severity have all been mitigated, perhaps due to extra focus being placed on these areas.

5 Discussion

The study developed a simplified DT for monitoring modular construction using IoT-integrated 3D models. A custom ontology structured the system around key element life-cycle stages, with DT interfaces enabling real-time data synchronisation to provide an autonomous progress monitoring solution. A fictitious case study demonstrated the system, using QR and RFID technologies for accessibility and clarity. The model focused on progress tracking up to element erection, aligning with

DT principles and extending 4D BIM capabilities. Microsoft Azure supported scalable deployment and continuous physical-digital connectivity. Validation through simulated data confirmed effective performance, with 3D visual updates reflecting element status. The case study revealed no need for iteration, indicating system robustness. Modular construction projects do not require a high degree of dimensional accuracy for on-site progress measurement as each element is produced to a predefined geometry, often created in 3D modelling software (Jiang, Li, Guo, et al., 2022). This avoids the issues of visual-based solutions, such as high costs and recognition failures (Wang et al., 2021).

The literature indicates that most DT solutions target traditional construction workflows (Jiang, Li, Guo, et al., 2022). A common requirement is the integration of high-fidelity BIM models (Alizadehsalehi & Yitmen, 2023a; Jiang, Li, Guo, et al., 2022; Lu et al., 2020), a challenge for modular construction, where DT development may be needed before BIM maturity is reached. This stems from fragmented BIM models typically being merged late in the pre-construction or construction project stages (Boje et al., 2020). Further investigation into enabling technologies led to IoT, revealing challenges such as device selection (Foroughi Sabzevar et al., 2023), cloud infrastructure (Fuller et al., 2020), and compatibility (Rasheed et al., 2020). Utilisation of IoT platforms mitigates some of these challenges, offering cost-efficient deployment (Liu et al., 2021). RFID tags were frequently cited in manufacturing and progress monitoring applications (Kokuryo et al., 2016; Oztemel & Gursev, 2020). Their use in progress monitoring (Cheng & Chang, 2001; Jiang, Li, Guo, et al., 2022) and 4D BIM solutions (Boje et al., 2020) supports their integration in modular construction monitoring.

DTs are well-suited to modular construction due to its manufacturing-driven nature, aligning with DT applications in production environments (Liu et al., 2021; Rasheed et al., 2020). While manufacturing DTs monitor production systems, DTs in modular construction focus on the element's life-cycle up to site erection. Digitisation enables integration across fragmented processes (Boje et al., 2020; Fuller et al., 2020; HM Treasury, 2015; Rasheed et al., 2020), including modular construction. Literature highlights DTs' potential to improve coordination in modular projects (Aldabbas, 2023; Jiang, Li, Guo, et al., 2022; Jiang, Li, Li, et al., 2022), supporting collaborative progress monitoring. The developed artefact confirms that DT-based progress monitoring in modular construction is feasible and effective. Utilising cloud platforms ensures user accessibility and supports collaboration, which enhances project planning and management (Dong et al., 2022).

5.1 Implications for Industry

This paper demonstrates that DT concepts can be integrated with modular construction projects to provide a progress monitoring solution, enabled by instantaneous and automated element status updates. Examination of similar systems indicated such a solution may be viable, informing the later choices during the development of the solution by presenting key challenges of such solutions. Challenges relating to visual data collection (Hannan Qureshi et al., 2022) could be mitigated by using limited data collection using rudimentary devices enabled by fixed geometric progression due to project subdivision into modular elements. This was found to be a benefit of modular construction held over traditional methods (Jiang, Li, Guo, et al., 2022), allowing for use of basic IoT devices such as RFID tags. Exploration of the key areas related to the subject matter led to discovery of the similarities the topic shares with 4D BIM, and the significant role it is playing in improving progress monitoring within industry (UK BIM Framework, 2019). This paper presents an evolution from 4D BIM to a DT for progress monitoring, using integration of IoT devices (Elghaish et al., 2022), providing insights for industry of the opportunities of pursuing such an evolution.

The establishment of a working solution demonstrates to industry that such solutions are both plausible and practical. With multiple third-party providers of cloud DT services (Radanliev et al., 2022; Rasheed et al., 2020) these technologies have become more accessible and cost effective. Using one of these providers, namely Microsoft Azure, to develop the solution introduced an ease of individual customisation to the solution, inviting the opportunity for end users to align their strategic goals with the solution. The development of a novel ontology for modular projects progress monitoring presents industry with a foundation to create their own DTs on a service best suited to their requirements, with mechanisms aligned with their goals. Given the rapid growth of Industry 4.0 (Oztemel & Gursev, 2020) and the built environments need to keep up (HM Treasury, 2015), embracing new growing technologies like DTs is essential to the development of the industry (Radanliev et al., 2022; Zambrano et al., 2022). In conclusion, this research highlights the need and significance of technology in modern construction, presenting a DT solution for industry to advance the field of modular progress monitoring.

6 Conclusion

This research developed an autonomous progress monitoring solution for modular construction using DT concepts to overcome limitations in current methods. As modern projects grow in scale and complexity, traditional monitoring becomes less effective, necessitating adaptable digital systems. Literature insights shaped research objectives focused on practical implementation and scalability. A DSR methodology guided the structured development and case study evaluation of the solution. While effective in iterative problem-solving, validation was limited to a simulated environment. Further assessment on live projects is needed to confirm real-world applicability.

Creation of a novel ontology for modular construction progress monitoring DTs was an additional output of this objective, in addition to the generation of the solution using Microsoft Azure. Achieved through evaluation of the proposed artefact, the solution was found to provide an effective platform for generation of unique DTs for modular construction progress monitoring. No substantial areas of improvements were identified, with positive results observed. The practicality of the solution was assessed; findings indicated a viable and practical DT solution for modular construction projects was created. Part of this objective was to make improvements to the solution; however no substantial improvements arose to warrant another iteration of the process. The research presents some significant insights to the construction industry, academics, and practitioners. The key implications and recommendations are: A DT for modular construction progress monitoring presents a plausible and practical solution to the demands of modern construction. Due to the digitisation of the industry, integration of DTs to other areas may also present benefits. The paper presents an ontology for the creation of modular construction progress monitoring DTs, one that can be adapted to suit the individual needs of end users. The mechanisms presented in the solution provide a basis for evolution of the proposed solution.

A limitation of this research is the simulation of data, to thoroughly evaluate the solution an active project would be beneficial. Another limitation is the use of Microsoft Azure to host the twin. Using provider platforms introduces concerns regarding data ownership and security. Future research might consider evaluating the robustness of the solution by creating twins on platforms from different providers, assessing strengths and weaknesses of each. Another next step may be application of the solution to a real-world modular construction project, making comparisons between traditional progress monitoring and the proposed solution. If the solution was to be researched further, investigation into the shortcomings found in the evaluation, such as perceived security and privacy should be addressed. In addition, research into the scalability of the platform would be beneficial.

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The study was conducted in accordance with established standards for research integrity and ethics.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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