Impact of emerging digital technologies on offsite construction: insights from literature

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Abstract
The implementation of emerging digital technologies such as 3D printing and blockchains into offsite or modular construction can facilitate the wider acceptance of this modern method of construction. This study aims to analyse the impact of emerging digital technologies on offsite construction. A literature review was conducted in this research to reveal the benefits of emerging technologies. The digital technologies examined in this study having innovative impact on offsite construction are 3D Printing, Internet of Things, Extended Reality, Artificial Intelligence, Robotics, Blockchain, Laser Scanners and Photogrammetry, and Digital Twins. Adopting digital technologies in offsite construction can improve design and planning, increase efficiency and productivity, enhance quality and safety, and increase sustainability.

Keywords
Offsite construction, Digital technologies, Review of literature, Modular construction, Industry 4.0

1. Introduction

Offsite construction, also known as prefabricated construction, panelised construction or modular construction refers to the completion of building components in a factory before they are moved to a different location where they will be installed in their final location (Staib et al., 2017) (Christopher Rausch et al., 2019) (Altaf et al., 2018) (Zoloedova et al., 2017). This method of construction has increased in popularity in the last two decades, however offsite construction adoption is still hindered due to several issues such as inflexibility in design change, long design times, lack of quality inspection and low supply change efficiency (W. Zhang et al., 2018).

The adoption of emerging digital technologies has proven its benefits in several industries including manufacturing (M. Yang et al., 2021) (Blichfeldt & Faullant, 2021)(Rodríguez-Espíndola et al., 2022) and construction (Mannino et al., 2021).

The combined outcomes of those digital transformation that trigger new developments in industries is part of the industry 4.0 or fourth industrial revolution. The main technology enablers include the Internet of Things (IoT), artificial intelligence, and visualisation (Szalavetz, 2019). The use of these technologies paired with Building Information Modelling (BIM) has become fundamental to the enhancement of a collaborative and efficient planning and design of construction projects including offsite construction (D Lee et al., 2021).

There is a growing interest in the adoption of digital technologies in offsite and prefabricated construction explaining the theories and their applications (Cheng et al., 2023). In general, the existing research have proven that digital technologies can improve efficiency of offsite construction (M. Wang et al., 2022) (M. Wang et al., 2020). The aim of this research is to analyse the impact of emerging digital technologies on offsite construction. This will be achieved by identifying the key digital technologies that are currently used in offsite modern methods of construction. The study will then focus on the benefits of integrating technologies that have been displayed in the literature.

2. Methodology

A brief literature review is conducted in this study to examine the impact of emerging digital technologies on offsite construction. The keywords used for data collection include “Digital technologies” AND “off-site construction” OR “modular construction” OR “prefabrication construction” OR “modular integrated construction” OR “modular buildings” OR “prefabricated building” OR “offsite construction” OR “volumetric construction.” OR “panelized construction”. The keywords were used to generate search strings to discover relevant papers. The resulting articles were filtered by only including “journal” and “conference” papers to ensure the quality of the study. Further manual screening was performed by reading the title and abstract to remove unrelated articles. Out of the plethora of papers found, only 41 were selected for this research as displayed in table 1 with the corresponding digital technology. The key digital technologies influencing offsite construction were identified by thoroughly studying the results of the literature screening. Furthermore, a survey was conducted among construction professionals experienced in modern methods of construction. The questionnaire was sent to nearly 190 participants using LinkedIn messaging and emails and 14 responses were received. Although the response rate is low compared to other industrial surveys, however, there is a noticeable decline in responses in recent years particularly for online surveys compared to paper based counterparts (M. J. Wu et al., 2022). This will be taken into consideration for forthcoming research. Figure 1 displays a word cloud of the digital technologies that the participants foresee being used in the near future. It can be observed BIM got the highest number of votes reflected by the larger font size followed closely by Unmanned Aerial Vehicles (UAVs) or drones. Real-time data, robotics and artificial intelligence are among those mentioned.

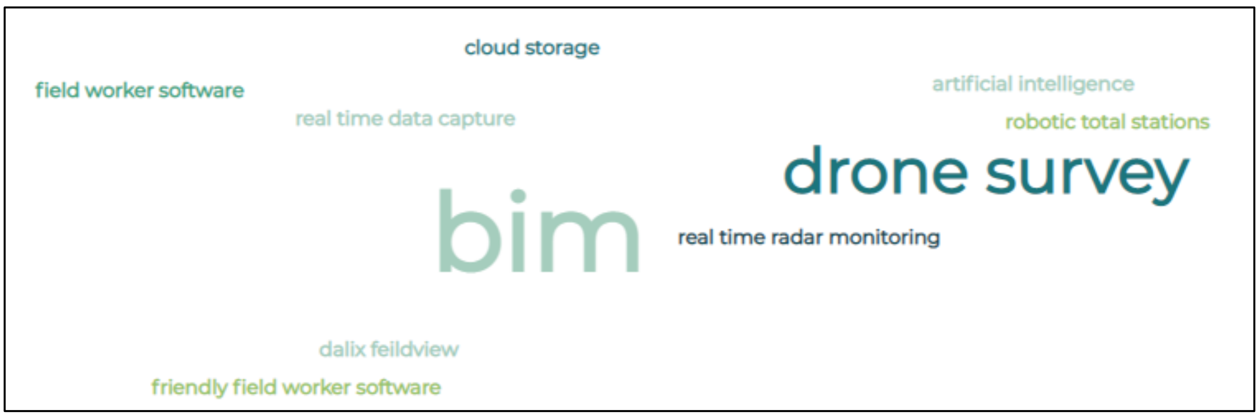

Figure 1- Digital technologies participants forecast to be used in the near future

3. Results

The success of offsite construction methods depend immensely on adopting digital technologies, however a study conducted in 2020 found that only 12.8% of the overall research published around offsite construction involves digital technologies (M. Wang et al., 2020). Moreover, the survey conducted as part of the current study reveals that only 28% of the respondents have heard of the term “industry 4.0”. This indicates that the concepts used in academia are not being addressed as part of the continued professional development in the industry.

Several technologies are greatly aiding the development of offsite construction underpinned by BIM processes, from extended reality to 3D printing. Presented below are the potential benefits and likely influences of using these technologies in offsite construction. Table 1 displays a summary of the likely outcomes of those technologies.

<u>3D Printing</u>

3D printing is one of the most essential tools of industry 4.0 (Jandyal et al., 2022). It supports sustainability as it saves time and cost compared to traditional methods of construction (Han et al., 2020) as well as noticeably lowering labour cost (Y. He et al., 2020; H. Yang et al., 2018). It is evident from the literature that 3D printing reduces the cost of formwork as 3D concrete printing does not use supporting formwork (Paul et al., 2018) especially for geometrically uneven buildings (Y. He et al., 2020).

Internet of Things (IoT)

Internet of Things (IoT) is a powerful paradigm that has been widely adopted in off-site construction (L. Wu et al., 2022)(Razkenari et al., 2020). IoT sensors and devices can provide the ability for real-time monitoring of the construction site and equipment (Gbadamosi et al., 2019)(Aisyah Jaafar et al., 2021), which enables detecting process abnormalities in turn optimising the construction implementation process (Yuan et al., 2021). Real- time data can also be used to track the movement of materials and equipment throughout the supply chain (Kazmi & Sodangi, 2022)(Hussein et al., 2021). This helps predict potential logistic risks enabling effective supply chain coordination (Dongmin Lee & Lee, 2021). Moreover, IoT sensors have been used for quality control purposes of prefabricated buildings through offsite construction (Yao et al., 2021). The integration of this real-time data with Building Information Models can help improve the efficiency, accuracy (G. Xu et al., 2018)(C. Z. Li et al., 2016) and safety (Teizer et al., 2017) of offsite construction.

Extended reality

Extended reality (XR) includes several immersive technologies that transform reality by adding virtual experiences to the real-world environment. It includes virtual reality (VR), augmented reality (AR) and mixed reality (MR) (Alizadehsalehi et al., 2020). AR technology can be combined with BIM models and data to optimise the design and planning processes allowing architects and other project stakeholders to share viewings. It can also be used for the confirmation of construction management information through visualisation during the construction phase (Chung et al., 2021). AR also helps reduce on-site error and possibilities of rework (Gimeno et al., 2018), as well as aiding inspection of prefabricated buildings (García-Pereira et al., 2020). MR method is also used for off-site construction supervision with the aid of BIM data and drone videos (Raimbaud et al., 2019).VR tools play in role in enhancing safety as well through visualising crane lifting paths to avoid any collisions that might occur (Z. Zhang & Pan, 2019).

Artificial Intelligence

AI implies using machines to model intelligent behaviour such as reasoning, learning and knowledge with minimal human intervention (Mohammadpour et al., 2019). It is a broad field that includes Machine Learning (ML) and Deep Learning (DL). These technologies helps industry practitioners in offsite manufacturing to make better decisions (Hwang et al., 2018), whether it be quality control during the assembly process (Arashpour et al., 2019), assisting decision makers to improve project planning and control through cost-time adjustments (Hamdan et al., 2016) or enabling better estimation of transportation costs for panelised construction projects (Ahn et al., 2020). Similarly AI combined with BIM technology can be used to automate designs resulting in time saving for the offsite process (H. Liu et al., 2018). ML techniques have been used in aiding in Offsite assembly (Tuvayanond & Prasittisopin, 2023) (Abioye et al., 2021). In terms of safety of construction workers AI technology has been researched in monitoring crane operators physical conditions and alerting them in signs of fatigue during the prefabricated assembly process (X. Li et al., 2019).

Robotics

Robotics have been increasingly used in recent years within the manufacturing industry. This has prompted construction practitioners to explore robotics potential in both onsite and offsite construction (M. Tehrani et al., 2022). Robotics have proven to increase production rates while reducing overall cost (Tehrani et al., 2022). Researchers have also explored the use of robots in construction waste sorting (Chen et al., 2022). BIM authoring tools have been utilised to aid robots in performing designated tasks that need explicit information, this approach has the potential of reducing errors from design to build in the construction industry (Wong Chong et al., 2022). Similarly, BIM is used within offsite construction systems for Construction automation purposes. Allowing the development of a design to manufacturing framework (Anane et al., 2023).

Blockchain

Blockchain technology can be used in offsite construction for supply chain management (Xiao Li et al., 2021) and for improving traceability (Z. Wang et al., 2020). It is combined with IoT systems to ensure construction material origin through tracking and tracing to avoid false material (J. Xu et al., 2023). Blockchain is also integrated within digital twins specifically to oversee fit-out operations in modular integrated construction (Jiang et al., 2023). However, this is still a work in progress and has not proven efficiencies in cost reduction.

Laser Scanners and Photogrammetry

Laser scanners have gained popularity in recent years as measuring tools in the construction industry (Bassier et al., 2016). Those methods of 3D scanning are used to model the terrain of the construction site directly developing 3D point clouds at high levels of accuracy (C Rausch et al., 2021). Both laser scanning and photogrammetry can be utilised for that purpose (Zhen Liu & Deng, 2017). Those methods have been progressing in recent years integrating them within other digital technologies such as UAVs and BIM (Murtiyoso & Grussenmeyer, 2018). The integration of 3D laser scanning and BIM has displayed potential for modular construction quality control.

Digital Twins

Digital twin concept is used to optimise buildings performance throughout their lifecycle. This can be applied within prefabricated buildings to assist with data-driven decision making. Data can be collected from prefabrication procedures through IoT sensors, and then predictive analysis can be performed, optimising the control decisions for manufacturing facilities operations (R. He et al., 2021), or as an effective security management and decision making tool (Zhansheng Liu et al., 2021).

Table 1. Benefits of digital technologies in offsite construction

Digital Technology	Likely Outcomes	Relevant Literature
3D Printing	- Cost saving by decreasing cost of labour significantly - Time saving as it supports mass production - Improves accuracy by eliminating human error	(Paul et al., 2018) (Han et al., 2020) (Y. He et al., 2020) (H. Yang et al., 2018)
Internet of Things	- Monitoring of construction site and equipment - Supply chain management - Quality control - Safety by providing alerts for potential hazards	(Gbadamosi et al., 2019)(Aisyah Jaafar et al., 2021) (Yuan et al., 2021). (Kazmi & Sodangi, 2022)(Hussein et al., 2021) (Dongmin Lee & Lee, 2021).
Extended Reality	- Optimise design and planning processes - Confirmation of construction management information - Reduce on-site errors and possibilities of rework - Aiding inspection of prefabricated buildings - Off-site construction supervision - Enhancing safety through visualisation	(Yao et al., 2021) (Teizer et al., 2017) (Chung et al., 2021) (Gimeno et al., 2018) (García-Pereira et al., 2020) (Raimbaud et al., 2019) (Z. Zhang & Pan, 2019)
Artificial Intelligence	- Quality control - Improve project planning and control - Estimation of transportation costs for panelised construction projects - Enhance and automate the design practice - Optimise structural performance - Aiding Offsite assembly - Safety of construction workers	(Hwang et al., 2018)(Arashpour et al., 2019)(Hamdan et al., 2016) (Ahn et al., 2020) (Abioye et al., 2021) (H. Liu et al., 2018) (Baghdadi et al., 2020) (Tuvayanond & Prasittisopin, 2023) (Abioye et al., 2021)(X. Li et al., 2019)
Robotics	- Increase production rates - Reduce overall cost - Construction waste sorting - Reduce errors from design to build - Construction automation	(Tehrani et al., 2022) (Chen et al., 2022) (Wong Chong et al., 2022)
Blockchain	- Supply chain management - Improving traceability - Oversee fit-out operations - Project supervision	(Xiao Li et al., 2021) (Z. Wang et al., 2020) (J. Xu et al., 2023) (Jiang et al., 2023) (R. Yang et al., 2020)

Laser Scanners and Photogrammetry	- Quality control - Improve dimensional quality - Geometric quality inspection - Improving safety	(H. Li et al., 2020)(Christopher Rausch et al., 2020) (Guo et al., 2020) (Goh et al., 2019) (Gilmour & Stroulia, 2022)
Digital Twins	- Assist with data-driven decision making - Effective security management	(R. He et al., 2021) (Zhansheng Liu et al., 2021)

4. Discussion

This research aimed to analyse the impact of emerging industry 4.0 enabling technologies that are most commonly used in offsite construction. This was achieved by first highlighting the emerging technologies and respectively displaying their benefits as can be seen in figure 2. The use of digital technologies has proven improvements in many aspects of offsite construction. For example, compared to conventional methods of construction, 3D printing technology enables cost and time reduction (Han et al., 2020) as well as significantly reducing labour costs (Y. He et al., 2020; H. Yang et al., 2018). It is also clear from the above results that 3D printing reduces the cost of formwork as 3D concrete printing does not use supporting formwork (Paul et al., 2018) especially for geometrically uneven buildings (Y. He et al., 2020).

Another aspect that displays potential is the increased efficiency of supply chain coordination and management. IoT can track the movement of materials and equipment (Kazmi & Sodangi, 2022)(Hussein et al., 2021), this helps predict potential logistic risks enabling effective supply chain coordination (Dongmin Lee & Lee, 2021). Combined with blockchain technology it can improve traceability (Xiao Li et al., 2021) (Z. Wang et al., 2020). In terms of safety, it can increase considerably by the use of real-time data integrated in BIM models (Teizer et al., 2017), as well as enhancing the safety of crane lift operations through VR, AI and laser scanning technologies (Z. Zhang & Pan, 2019)(X. Li et al., 2019)(Goh et al., 2019).

Adoption of smart technologies such as IoT sensors, AI and 3D laser scanning enables better methods of quality control of offsite projects, whether it is during the project planning or assembly process (Yao et al., 2021)(Arashpour et al., 2019). Furthermore, those technologies can improve the accuracy of conducting offsite projects through the integration of real-time data with BIM (G. Xu et al., 2018), moreover 3D scanning is used to model the terrain of the construction site directly developing 3D point clouds at high levels of accuracy (C Rausch et al., 2021) compared to traditional methods of surveying. Robotics and the use of BIM authoring tools can aid in performing designated tasks that need explicit information, and the approach has potential of reducing errors from design to construction.

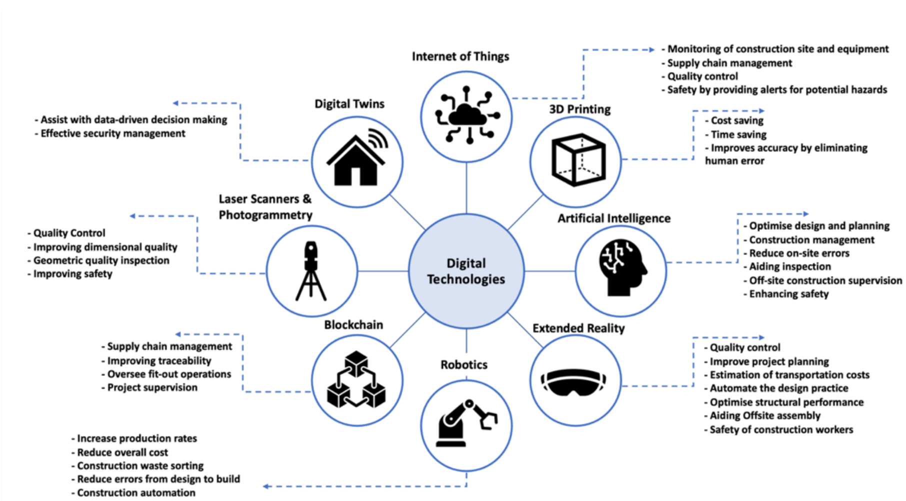

Figure 2- Applications of digital technologies in offsite construction

5. Conclusions

The purpose of this present study is to investigate the impacts of digital technologies on offsite construction. A succinct literature review is carried out along with an online survey of industry professionals. The identified technologies include 3D Printing, IoT, XR, AI, Robotics, Blockchain, Laser Scanners and Photogrammetry, and Digital Twins. The investigation revealed significant impact of emerging digital technologies on offsite construction in key areas such as:

1- Improved design and planning: For example, through artificial intelligence and extended reality.

2- Increased efficiency and productivity: For instance, robotics and automation systems have the ability to perform repetitive tasks. 3D printing plays a role in improving accuracy and eliminating human errors.

3- Enhanced quality and safety: the use of sensors powered by IoT systems enables monitoring of conditions of equipment and material of construction sites. Extended reality can also be used to train workers and aid them in offsite assembly, helping them to detect potential hazards consequently improving the overall safety awareness.

4- Increased sustainability: 3D printing can be used to create components with minimal waste, as well as saving cost and time. Robotics and automation can also reduce the environmental footprint by reducing errors from design to build and reducing overall cost.

This review raises theoretical and practical implications, it serves as a guide for future researchers to understand the current state of impact of digital technologies on offsite construction. It also contributes for industry professionals as it offers information on technologies that can be employed in the process of digitization of offsite construction.

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