UNB EST. 1785 UNIVERSITY OF NEW BRUNSWICK | Off-site Construction Research Centre

Northumbria University NEWCASTLE

Transforming Construction with Off-site Methods and Technologies (TCOT) Conference: Designing Tomorrow's Construction, Today

August 20-22, 2024, Fredericton, New Brunswick, Canada

Smart Technologies for Modular Construction: A Review of Current Applications

Hasan, Sibgat Mehedi[1], Choi, Jin Ouk[2*], and Shahi, Amrit[3]
[1] Department of Civil and Environmental Engineering and Construction, Univ. of Nevada, Las Vegas, NV.
[2]Associate Professor, Dept. of Civil and Environmental Engineering and Construction, Univ. of Nevada, Las Vegas, Las Vegas, NV.
[3] Department of Civil and Environmental Engineering and Construction, Univ. of Nevada, Las Vegas, NV.
[*]jinouk.choi@unlv.edu

Abstract: Modular construction has been around for a while, but it has been limited in its application. Recently, it has gained momentum due to the emergence of smart technologies that address technical and management challenges, enhance quality and safety, and save time and money. This study reviews and highlights the existing smart technologies used in modular construction throughout a modular project's lifecycle to understand the application areas, benefits, impediments, and research regarding smart technologies in the modular construction field. The review involved a three-step procedure for selecting smart technologies applicable to the modular construction industry. First, a list of smart technologies related to modular construction was selected from the Modular Building Institute's industrial magazines and from the Autodesk company site. Second, a literature review was conducted using specific keywords. Finally, articles were screened based on relevance. The smart technologies identified include blockchain, computer vision, digital twin, generative design, VR, 4D BIM schedule, and robotic arms. The findings will help researchers and practitioners interested in modular construction to 1) better understand how smart technologies are used and help modular construction and 2) further use or develop them to improve the modular construction industry sector.

Keywords: Modularization, Offsite, Preassembly, Smart Technology

1 INTRODUCTION

Modularization is a strategy that has been used for hundreds of years to move part of the work from the site to the fabrication/assembly shops or yards (Choi et al. 2019). Depending on the project type, scale, location, logistics, and distance from fabrication shops, the level of prefabrication can range from small portions to substantial quantities (O'Connor et al. 2014). The advantages of modular construction include increased accuracy in building element construction, enhanced worker safety, accelerated construction process, and increased productivity (Choi et al. 2019). However, despite the numerous advantages, a significant issue with modular construction is that module fabrication and assembly are predominantly performed by people in a factory (Lee et al. 2022). Therefore, it is important that the modular construction industry implement smart and innovative technologies to improve productivity by automating more work in all project phases.

The following literature review provides a comprehensive overview of smart technologies and their applications in the modular construction industry. This study identifies the applications of smart technologies, their benefits, degree of technological maturity, obstacles, and relevant research demonstrating these smart technologies. The following review will help future researchers and practitioners to understand the smart technologies used in modular construction and will help them to improve the modular construction industry through these technologies.

2 METHODOLOGY

The following literature review establishes a three-step procedure for selecting smart technologies applicable to the modular construction industry. The first step involves selecting a list of technologies based on two main sources: the Modular Building Institute's industry magazines and the smart technologies featured in scholarly articles by Autodesk related to modular construction. After evaluating the list of technologies, the authors chose the following smart technologies for the review: 4D BIM schedule, computer vision, virtual reality (VR), Blockchain, digital twin, factory robotic arms for module fabrication, and generative design. The second stage entails searching for scholarly articles using a list of keywords, including "modular construction," "offsite construction," "4D BIM," "virtual reality," "BIM," "digital twin," "blockchain," "computer vision," "robotics," and "generative design." The scholarly articles were selected from a range of databases such as Google Scholar, Scopus, and the UNLV databases. Subsequently, a comprehensive literature review was conducted of various peer-reviewed journals and publications, such as the Journal of Building Engineering, Journal of Computing in Civil Engineering, Automation in Construction, and International Journal of Industrialized Construction, for the chosen smart technologies and their implementation in the modular construction industry. Lastly, the authors screened the titles and abstracts of the number of selected articles to include only those articles that provided useful information on application areas, benefits, technological maturity, obstacles, and relevant research related to smart technologies in the field.

3 LITERATURE REVIEW

3.1 4D BIM Schedule

In the context of the modular construction process, there are various stages in which smart technologies can be utilized. One such technology is the 4D BIM Schedule, which plays a significant role in the planning and design phase. 4D scheduling combines 3D BIM and a construction schedule to simulate the construction/fabrication sequence of a project from start to finish (Kim et al. 2013). This 4D simulation, which connects process data to a 3D model based on parametric data, can enable the visualization of construction data, such as processes and resources (Lee and Kim 2017)**.** The implementation of 4D BIM scheduling brings several benefits to modular construction. Firstly, it improves the planning and administration of the construction process. Additionally, 4D visualization technology exploits the complex relationships between entities to expedite processes and reduces or eradicates non-value-adding activities (Lee and Kim 2017). 4D BIM also provides construction teams with extractable information for specific purposes by designating the locations and times of activities or entities (Tran et al. 2022). However, despite its potential benefits, the application of 4D BIM in modular construction does pose some challenges.

For instance, the complex design works in a prefabricated project can be challenging for the use of 4D BIM in modular construction compared to conventional projects (Ahmadi and Arashpour 2020). Despite the challenges involved, the application of 4D BIM has been explored by several researchers. For instance, Ghimire et al. (2021) applied a 4D BIM schedule along with immersive virtual reality on a modular project. Additionally, 4D BIM was applied to mitigate the project risks involved in the planning phases of a project in the Netherlands involving the canal lock expansion (Sloot et al. 2019).

3.2 Computer Vision

Another smart technology explored in this review is computer vision. Computer vision involves the use of sensors, theoretical concepts, and algorithms that replicate some functions performed by the human visual system in an independent manner (Huang 1996). According to the number of studies related to computer vision, computer vision technology has recently gained significant interest in modular construction (Panahi et al. 2023).

Computer vision has several benefits in modular construction, including tracking of volumetric units (Panahi et al. 2022), acquiring productivity-related data (Alsakka et al. 2023), progress monitoring (Zheng et al. 2020) and quality control (Bae and Han 2021). However, computer vision does pose some challenges in the field of modular construction. Computer vision application is tricky for cluttered scenes with multiple occlusions, which are prominent characteristics of modular factories as a fast-paced, dynamic work environment (Panahi et al. 2021). Despite the challenges involved, researchers have explored computer vision in different phases of modular construction. For the fabrication phase, Panahi et al. (2023) discussed the computer vision-based method to identify the bottleneck station on the production line of modular construction factories. Panahi et al. (2021) explored the use of computer vision-based techniques to recognize the activities modular construction workers perform during the installation phase, while Panahi et al. (2024) investigated the assembly progress monitoring in the installation phase of subassemblies of modular construction using computer vision.

3.3 Virtual Reality (VR)

In the modular construction industry, another smart technology, such as virtual reality can be utilized in the planning phase. Virtual Reality (VR) is a computer-generated interactive environment that allows users to experience it as if they are in the environment (Kinateder et al. 2014). This technology has multiple applications in the modular construction industry, including planning the lifting of heavy mobile cranes (Kayhani et al. 2018); collaborative training in crane lifting (Zhang et al. 2023) and interactive layout planning (Zhang and Pan 2021). VR also has several advantages in modular construction. Virtual reality technologies aid in planning, design, construction, and project management (Wang et al. 2004); workspace conflict development (Moon et al. 2014); and construction education (Wang 2007).

The adoption of VR in the modular industry does pose some challenges. For example, VR is perceived as an immature technology that cannot be fully utilized in practice yet (Davila Delgado et al. 2020). Despite the obstacles, researchers have explored the use of VR in modular construction. For example, (Zhang and Pan 2021) developed a site layout planning tool for high-rise modular buildings using VR technology.

3.4 Blockchain

Blockchain is another technology that can be utilized in the planning phase of modular construction. Blockchain technology is a decentralized, peer-to-peer, distributed network ledger that enables trustworthy information sharing by providing an immutable digital footprint to all network participants (Wan et al. 2020). Blockchain application areas in modular construction include supply chain management, payment processing, and asset management (Wang et al. 2020). In SCM, for example, Tezel et al. (2021) and Elghaish, Abrishami, and Hosseini (2020) utilize blockchain technology for payments, proposal tendering, and asset tokenization.

Blockchain in modular construction has several benefits. For instance, Blockchain enables the formation of a decentralized organization where all network participants can interact, communicate, and reach a consensus without requiring a trusted authority (Lee et al. 2022). As materials transition from the prefabricated production phase to the on-site assembly, relevant data may be accessible in a decentralized manner, providing all stakeholders with confidence (Olawumi et al. 2022). Also, smart contracts provide expedited execution of relevant transactions and verification in modular construction using blockchain (Olawumi et al. 2022, Rashid and Siddique 2019), allowing blockchain to lead to increased communication and information sharing (Li et al. 2021). Despite the benefits, there are some impediments in the utilization of blockchain in modular construction. One significant challenge in hindering its adoption is financial constraints (Zhang et al. 2023). Furthermore, it is difficult to determine whether the shared information is sufficiently robust against malevolent manipulation or reliable enough for decision-making, given that conflict-of-interest-driven stakeholders may conceal, control, or modify crucial information (Lee et al. 2022).

Despite the challenges, block chain has been explored by researchers in modular construction. In the design phase, for example, Lee et al. (2022) showcased the utilization of a hybrid blockchain system, combining on-chain and off-chain elements, to ensure secure and traceable information sharing, enabling unrestricted data exchange and data-driven automated decision-making in the context of a Volumetric Modular Construction. Moreover, Jiang et al. (2021) presented a proposal for a cyber-physical smart modular integrated construction platform that utilizes blockchain technology to enable information exchange across numerous stakeholders from different enterprises.

3.5 Digital Twin

Digital twin is another smart technology that presents a promising avenue for the design phase of modular construction. A digital twin refers to a virtual representation of an object or system utilized to gather insights and predict potential issues throughout its entire lifecycle (Lee and Lee 2021). Unlike Computer-Aided Design (CAD) and IoT, which solely concentrate on the digital realm and the physical world, respectively, digital twins are characterized by their interactive nature, facilitating bidirectional interactions between the digital and physical domains, leading to numerous benefits (Tao et al. 2019). For example, one notable advantage of digital twin technology lies in its capacity to align sustainability goals with design objectives by proactively revealing carbon footprint and energy efficiency considerations during the initial stages (Patterson and Ruh 2019). Digital twin also improves the safety risk management of modular construction (Liu et al. 2021). Furthermore, it has the potential to reduce both time and costs associated with the construction process (Patterson and Ruh 2019).

Because digital twin technology is relatively novel in the modular construction industry and still in its infancy (Patterson and Ruh 2019), it faces certain challenges. The challenges include difficulties in investing in digital twin technology due to the small scale of projects and the lack of visibility into product-to-market timing (Patterson and Ruh 2019).

Despite these challenges, researchers have explored the applications of digital twin technology in modular construction. For instance, Lee and Lee (2021) conducted a study to develop and test a digital twin framework for real-time logistics and simulation in modular construction. Furthermore, Jiang et al. (2022) introduced a digital twin-enabled smart MiC (Modular Integrated Construction) system, employing a robotic testbed demonstration to optimize on-site assembly in prefabricated construction. Lee and Lee (2021) presented a digital twin architecture to enhance project scheduling by predicting the arrival time of modules. On the other hand, Ayinla et al. (2021) suggested an ontology knowledge structure to depict the production process for off-site manufacturing.

3.6 Robotic Arms

Robotics are increasingly being employed in module fabrication. In particular, robotic arms specifically have found applications in the construction industry. Numerous methods exist to automate modular manufacturing, but it can be argued that robotic arms are the most effective approach (Lee et al. 2022). Robotic arms in modular construction have several applications. They can be used for assembly planning (Munoz-Morera et al. 2015) and robotic prefabrication of wood frame modules (Willmann et al. 2016). One advantage of utilizing robotics in this context is its ability to ensure higher construction accuracy while performing tasks with greater precision and minimal errors (Sun et al. 2022). The implementation of robotics in module fabrication not only enhances structural performance and reduces material waste but also improves labor safety (Lee et al. 2022).

The scarcity of research related to this technology might pose challenges for industry leaders considering its adoption. Despite these challenges, researchers have made efforts to apply robotics in the fabrication phase of modular construction. For example, Sun et al. (2022) focused on using robotic arms to assemble overall modules and has integrated the concept of robotic arms into the building design process under extreme conditions such as cold environments. Furthermore, Song et al. (2022) discussed the current state of industrial robotic arms in modular construction and outlined this technology’s future.

3.7 Generative Design

Generative Design, as outlined by Villaggi and Nagy (2020), employs algorithmic and parametric modeling techniques to autonomously investigate, refine, and optimize design alternatives by establishing high-level constraints and objectives. This approach finds diverse applications across various domains**.** For example, a BIM-based generative workspace enables user interactions that encompass decision mechanisms and design rules (Abrishami et al. 2021). The flexibility and parameterization of generative design make it particularly suitable for manufacturing production processes involving the repetitive creation of products (Banihashemi et al. 2018, Pasetti Monizza et al. 2018). Modular construction, by its very nature, aligns with the requirements of manufacturing-based production, thus serving as an ideal fit for generative design (Wei et al. 2022)**.**

While the use of generative design in modular construction varies, it does present some obstacles. One identified obstacle to its adoption, as highlighted by Ma et al. (2021), pertains to the lack of comprehensive elements and diversity of design scenarios. Nevertheless, certain researchers have explored the potential applications of generative design in modular construction. For instance, Wei, Choi, and Lei (2022) have proposed a novel approach that integrates generative design with BIM technologies to address module layout generation, taking into consideration design and constructability constraints.

4 CONCLUSION AND RECOMMENDATION

This literature review explores the integration of smart technologies in the modular construction industry and identifies that progress has been made in integrating them; however, greater emphasis on innovation is needed. The modular industry holds substantial potential for the incorporation of intelligent technologies such as robotic arms, digital twin, generative design, 4D BIM, and blockchain as these technologies are maturing. This paper’s objective is to contribute to the industry by providing valuable insights to researchers and practitioners interested in understanding smart technologies’ application and development in the modular construction sector. Nonetheless, it is important to acknowledge this study’s limitations. Firstly, the scarcity of research on smart technologies in modular construction is a constraint. Additionally, the omission of certain technologies in accordance with the selection criteria further limits the scope of this investigation. Therefore, it is recommended that future research endeavors encompass: 1) a wider range of smart technologies and their respective applications; and 2) surveys, interviews, and case studies to better understand the current gain a more comprehensive understanding of their potential benefits.

5 REFERENCES

Abrishami, S., Goulding, J., and Rahimian, F. 2021. Generative BIM workspace for AEC conceptual design automation: prototype development. Engineering, Construction and Architectural Management, **28**(2): 482–509. Emerald Group Holdings Ltd. doi:10.1108/ECAM-04-2020-0256.

Ahmadi, P.F., and Arashpour, M. 2020. An Analysis of 4D-BIM Construction Planning: Advantages, Risks and Challenges. *In* Proceedings of the 37th International Symposium on Automation and Robotics in Construction, ISARC 2020: From Demonstration to Practical Use - To New Stage of Construction Robot. International Association on Automation and Robotics in Construction (IAARC). pp. 163–170.

Alsakka, F., El-Chami, I., Yu, H., and Al-Hussein, M. 2023. Computer vision-based process time data acquisition for offsite construction. Automation in Construction, **149**: 104803. doi:https://doi.org/10.1016/j.autcon.2023.104803.

Ayinla, K., Vakaj, E., Cheung, F., and Tawil, A.-R.H. 2021. A Semantic Offsite Construction Digital Twin-Offsite Manufacturing Production Workflow (OPW) Ontology. *In* Proceedings of the Second International Workshop on Semantic Digital Twins co-located with the 18th Extended Semantic Web Conference (ESWC 2021).

Bae, J., and Han, S. 2021. Vision-Based Inspection Approach Using a Projector-Camera System for Off-Site Quality Control in Modular Construction: Experimental Investigation on Operational Conditions. Journal of Computing in Civil Engineering, **35**(5): 4021012. doi:10.1061/(ASCE)CP.1943-5487.0000978.

Banihashemi, S., Tabadkani, A., and Hosseini, M.R. 2018. Integration of parametric design into modular coordination: A construction waste reduction workflow. Automation in Construction, **88**: 1–12. Elsevier B.V. doi:10.1016/j.autcon.2017.12.026.

Choi, J.O., Chen, X. Bin, and Kim, T.W. 2019. Opportunities and challenges of modular methods in dense urban environment. International Journal of Construction Management, **19**(2): 93–105. Taylor and Francis Ltd. doi:10.1080/15623599.2017.1382093.

Choi, J.O., O'Connor, J.T., Kwak, Y.H., and Shrestha, B.K. 2019. Modularization Business Case Analysis Model for Industrial Projects. Journal of Management in Engineering, **35**(3). American Society of Civil Engineers (ASCE). doi:10.1061/(asce)me.1943-5479.0000683.

Davila Delgado, J.M., Oyedele, L., Beach, T., and Demian, P. 2020. Augmented and Virtual Reality in Construction: Drivers and Limitations for Industry Adoption. Journal of Construction Engineering and Management, **146**(7). American Society of Civil Engineers (ASCE). doi:10.1061/(asce)co.1943-7862.0001844.

Elghaish, F., Abrishami, S., and Hosseini, M.R. 2020. Integrated project delivery with blockchain: An automated financial system. Automation in Construction, **114**. Elsevier B.V. doi:10.1016/j.autcon.2020.103182.

Ghimire, R., Lee, S., Choi, J.O., Lee, J.-Y., and Lee, Y.-C. 2021. Combined Application of 4D BIM Schedule and an Immersive Virtual Reality on a Modular Project: UNLV Solar Decathlon Case. International Journal of Industrialized Construction, **2**(1): 1–14. University of Alberta Libraries. doi:10.29173/ijic236.

Huang, T.S. 1996. Computer Vision: Evolution and Promise. *In* 19th CERN School of Computing. pp. 21–25.

Jiang, Y., Li, M., Guo, D., Wu, W., Zhong, R.Y., and Huang, G.Q. 2022. Digital twin-enabled smart modular integrated construction system for on-site assembly. Computers in Industry, **136**. Elsevier B.V. doi:10.1016/j.compind.2021.103594.

Jiang, Y., Liu, X., Kang, K., Wang, Z., Zhong, R.Y., and Huang, G.Q. 2021. Blockchain-enabled cyber-physical smart modular integrated construction. Computers in Industry, **133**: 103553. doi:https://doi.org/10.1016/j.compind.2021.103553.

Kayhani, N., Taghaddos, H., Noghabaee, M., and Hermann, U. 2018. Utilization of Virtual Reality Visualizations on Heavy Mobile Crane Planning for Modular Construction. *In* 35th International Symposium on Automation and Robotics in Construction (ISARC 2018).

Kim, C., Kim, B., and Kim, H. 2013. 4D CAD model updating using image processing-based construction progress monitoring. Automation in Construction, **35**: 44–52. doi:10.1016/j.autcon.2013.03.005.

Kinateder, M., Ronchi, E., Nilsson, D., Kobes, M., Müller, M., Pauli, P., and Mühlberger, A. 2014. Virtual reality for fire evacuation research. *In* 2014 Federated Conference on Computer Science and Information Systems, FedCSIS 2014. Institute of Electrical and Electronics Engineers Inc. pp. 313–321.

Lee, D., and Lee, S. 2021. Digital Twin for Supply Chain Coordination in Modular Construction. Applied Sciences, **11**(13). doi:10.3390/app11135909.

Lee, D., Wen, L., Asce, S.M., Choi, J.O., Asce, M., and Lee, S. 2022. Sensor-Integrated Hybrid Blockchain System for Supply Chain Coordination in Volumetric Modular Construction. doi:10.1061/(ASCE)CO.1943.

Lee, J., and Kim, J. 2017. BIM-Based 4d simulation to improve module manufacturing productivity for sustainable building projects. Sustainability (Switzerland), **9**(3). MDPI. doi:10.3390/su9030426.

Lee, S., Choi, J.O., and Song, S. 2022. Cutting-edge Technologies to Achieve a Higher Level of Modular Construction-Literature Review. International Conference on Construction Engineering and Project Management 536-542.

Li, X., Wu, L., Zhao, R., Lu, W., and Xue, F. 2021. Two-layer Adaptive Blockchain-based Supervision model for off-site modular housing production. Computers in Industry, **128**: 103437. doi:https://doi.org/10.1016/j.compind.2021.103437.

Liu, Z., Meng, X., Xing, Z., and Jiang, A. 2021. Digital Twin-Based Safety Risk Coupling of Prefabricated Building Hoisting. Sensors, **21**(11). doi:10.3390/s21113583.

Ma, W., Wang, X., Wang, J., Xiang, X., and Sun, J. 2021. Generative design in building information modelling (Bim): Approaches and requirements. MDPI AG.

Moon, H., Dawood, N., and Kang, L. 2014. Development of workspace conflict visualization system using 4D object of work schedule. Advanced Engineering Informatics, **28**(1): 50–65. Elsevier Ltd. doi:10.1016/j.aei.2013.12.001.

Munoz-Morera, J., Maza, I., Fernandez-Aguera, C.J., Caballero, F., and Ollero, A. 2015. Assembly planning for the construction of structures with multiple UAS equipped with robotic arms. *In* 2015 International Conference on Unmanned Aircraft Systems (ICUAS). pp. 1049–1058.

O'Connor, J.T., O'Brien, W.J., and Choi, J.O. 2014. Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization. Journal of Construction Engineering and Management, **140**(6). American Society of Civil Engineers (ASCE). doi:10.1061/(asce)co.1943-7862.0000842.

Olawumi, T.O., Chan, D.W.M., Ojo, S., and Yam, M.C.H. 2022. Automating the modular construction process: A review of digital technologies and future directions with blockchain technology. Elsevier Ltd.

Panahi, R., Louis, J., Aziere, N., Ankur Podder, ;, Swanson, C., and Student, P.D. 2021. Identifying Modular Construction Worker Tasks Using Computer Vision.

Panahi, R., Louis, J., Podder, A., and Swanson, C. 2022. Tracking Volumetric Units in Modular Factories for Automated Progress Monitoring Using Computer Vision. *In* Construction Research Congress 2022. pp. 822–829.

Panahi, R., Louis, J., Podder, A., Swanson, C., and Pless, S. 2023. Bottleneck Detection in Modular Construction Factories Using Computer Vision. Sensors, **23**(8): 3982. doi:10.3390/s23083982.

Panahi, R., Louis, J., Podder, A., Swanson, C., and Pless, S. (ORCID:0000000310543757). 2024. Automated Assembly Progress Monitoring in Modular Construction Factories Using Computer Vision-Based Instance Segmentation. Reston, VA: American Society of Civil Engineers (ASCE), United States.

Pasetti Monizza, G., Bendetti, C., and Matt, D.T. 2018. Parametric and Generative Design techniques in mass-production environments as effective enablers of Industry 4.0 approaches in the Building Industry. Automation in Construction, **92**: 270–285. Elsevier B.V. doi:10.1016/j.autcon.2018.02.027.

Patterson, D., and Ruh, B. 2019. Voices on Infrastructure Scaling modular construction.

Rashid, A., and Siddique, M.J. 2019. Smart Contracts Integration between Blockchain and Internet of Things: Opportunities and Challenges. *In* 2019 2nd International Conference on Advancements in Computational Sciences (ICACS). pp. 1–9.

Sloot, R.N.F., Heutink, A., and Voordijk, J.T. 2019. Assessing usefulness of 4D BIM tools in risk mitigation strategies. Automation in Construction, **106**. Elsevier B.V. doi:10.1016/j.autcon.2019.102881.

Song, S.H., Choi, J.O., Lee, S., Song, S.H., Choi, J.O., and Ho Song, S. 2022. The Current State and Future Directions of Industrial Robotic Arms in Modular Construction. International Conference on Construction Engineering and Project Management 336-343.

Sun, Z., Mei, H., Pan, W., Zhang, Z., and Shan, J. 2022. A Robotic Arm Based Design Method for Modular Building in Cold Region. Sustainability (Switzerland), **14**(3). MDPI. doi:10.3390/su14031452.

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

Tezel, A., Febrero, P., Papadonikolaki, E., and Yitmen, I. 2021. Insights into Blockchain Implementation in Construction: Models for Supply Chain Management. Journal of Management in Engineering, **37**(4). American Society of Civil Engineers (ASCE). doi:10.1061/(asce)me.1943-5479.0000939.

Tran, S.V.T., Nguyen, T.L., Chi, H.L., Lee, D., and Park, C. 2022. Generative planning for construction safety surveillance camera installation in 4D BIM environment. Automation in Construction, **134**. Elsevier B.V. doi:10.1016/j.autcon.2021.104103.

Villaggi, L., and Nagy, D. 2020. Generative Design for Architectural Space Planning. Available from https://www.autodesk.com/autodesk-university/article/Generative-Design-Architectural-Space-Planning. [accessed 8 April 2023].

Wan, P.K., Huang, L., and Holtskog, H. 2020. Blockchain-Enabled Information Sharing within a Supply Chain: A Systematic Literature Review. IEEE Access, **8**: 49645–49656. Institute of Electrical and Electronics Engineers Inc. doi:10.1109/ACCESS.2020.2980142.

Wang, H.J., Zhang, J.P., Chau, K.W., and Anson, M. 2004. 4D dynamic management for construction planning and resource utilization. Automation in Construction, **13**(5 SPEC. ISS.): 575–589. Elsevier. doi:10.1016/j.autcon.2004.04.003.

Wang, L. 2007. USING 4D MODELING TO ADVANCE CONSTRUCTION VISUALIZATION IN ENGINEERING EDUCATION.

Wang, Z., Wang, T., Hu, H., Gong, J., Ren, X., and Xiao, Q. 2020. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Automation in Construction, **111**. Elsevier B.V. doi:10.1016/j.autcon.2019.103063.

Wei, Y., Choi, H., and Lei, Z. 2022. A generative design approach for modular construction in congested urban areas. Smart and Sustainable Built Environment, **11**(4): 1163–1181. Emerald Publishing. doi:10.1108/SASBE-04-2021-0068.

Willmann, J., Knauss, M., Bonwetsch, T., Apolinarska, A.A., Gramazio, F., and Kohler, M. 2016. Robotic timber construction — Expanding additive fabrication to new dimensions. Automation in Construction, **61**: 16–23. doi:https://doi.org/10.1016/j.autcon.2015.09.011.

Zhang, P., Wu, H., Li, H., Zhong, B., Fung, I.W.H., and Lee, Y.Y.R. 2023a. Exploring the adoption of blockchain in modular integrated construction projects: A game theory-based analysis. Journal of Cleaner Production, **408**. Elsevier Ltd. doi:10.1016/j.jclepro.2023.137115.

Zhang, Z., and Pan, W. 2021. Virtual reality supported interactive tower crane layout planning for high-rise modular integrated construction. Automation in Construction, **130**. Elsevier B.V. doi:10.1016/j.autcon.2021.103854.

Zhang, Z., Wong, M.O., and Pan, W. 2023b. Virtual reality enhanced multi-role collaboration in crane-lift training for modular construction. Automation in Construction, **150**. Elsevier B.V. doi:10.1016/j.autcon.2023.104848.

Zheng, Z., Zhang, Z., and Pan, W. 2020. Virtual prototyping- and transfer learning-enabled module detection for modular integrated construction. Automation in Construction, **120**: 103387. doi:https://doi.org/10.1016/j.autcon.2020.103387.