An investigation of digital technology implementation in off-site construction: current practice, challenges and expectations

Mudan Wang[1], Cynthia Changxin Wang[1*], Samad Sepasgozar[1] and Sisi Zlatanova[1]

[1] *School of Built Environment, University of New South Wales, Sydney 2052, Australia*
Email: mudan.wang@student.unsw.edu.au; cynthia.wang@unsw.edu.au; Sepas@unsw.edu.au; s.zlatanova@unsw.edu.au:

Abstract
Off-site construction has generally been regarded as a more productive construction method, and digital technologies are considered to provide higher productivity and safety. However, there is a lack of research on how digital technologies can be best utilized to achieve the potential advantages of off-site construction. Some literature has made exploration in this area, while first-hand investigations from the construction industry are still rare. This study aims to identify the issues which can be potentially resolved by adopting digital technologies in off-site construction projects, and investigate the current practice and possible approaches to improve the technology utilization to achieve the goal. Practitioners including designers, manufacturers and site engineers working in Chinese off-site construction projects were interviewed based on a semi-structured question, and qualitative analysis was carried out using thematic analysis to provide a taxonomy of technology utilisation in NVivo. 16 critical challenges and 16 main expectations are identified. BIM, photogrammetry, laser scanning, AR/VR are categorised as promising technologies with more strengths for future implementation. This study provides the directions of future studies on digital technology implementation from practitioners' perspective, which is of great practical and theoretical value for off-site construction industry.

Keywords
BIM, digital construction, off-site construction, technology implementation, technology utilization

1 Introduction

Off-site construction (OSC) has generally been regarded as a more productive and sustainable construction method, and many publications have summarized OSC's potential benefits in quality, productivity and sustainability (Chowdhury *et al.*, 2019, Wang *et al.*, 2019, Wang *et al.*, 2020, Kabirifar *et al.*, 2021). However, in the current practice, the performance of this construction method still encountered many challenges regarding time, labour and cost aspects due to more complex processes and stakeholders involved (Li *et al.*, 2016, Zhai *et al.*, 2019). Some research reported that the total time from design to onsite assembly could be longer than conventional construction (Liu *et al.*, 2018). In addition, the cost of prefabricated buildings was estimated 26.3% to 72.1% higher than that of conventional buildings (Arashpour *et al.*, 2018, Hong *et al.*, 2018). These facts indicated that many problems need to be solved to fully realize the potential benefits of OSC, and digital technologies are regarded as the key solutions to improve productivity in the construction industry (Maskuriy *et al.*, 2019, Alaloul *et al.*, 2020).

Some digital technologies have been reported that could improve the quality, reduce cost, save time and labour for OSC projects, such as building information modelling (BIM) (Sepasgozar *et al.*, 2016b, Yin *et al.*, 2019), radio frequency identification devices (RFID) (Luo *et al.*, 2020), laser scanning (Sepasgozar *et al.*, 2016a, Sepasgozaar *et al.*, 2017, Guo *et al.*, 2020), etc. Previous studies also made investigations of digital technology implementation for OSC. A systematic review of digital technology adoption in OSC have been conducted, and identified virtual reality (VR), augmented reality (AR), photogrammetry, laser scanning, and artificial intelligence (AI) are relatively less explored in OSC, but they are regarded as promising technologies to be very effective in improving OSC performance (Wang *et al.*, 2020). However, there is a lack of first-hand investigations from the construction industry towards digital technology implementation in OSC. Interviews are recognized as the most effective approach to gain deep knowledge of the construction industry (Jiang *et al.*, 2018). The interview manuscripts could be analysed based on NVivo which is a qualitative data analysis software (Adetoro Adewunmi and Damilola Ajayi, 2016, Samad and Steven, 2018).

Therefore, this study conducted an in-depth interview in OSC to explore the current practices of these available digital technologies, and how they can be utilized in contributing to fully achieve the advantages of OSC. Based on interview data analysis, this research aims to identify the issues which can be potentially solved by adopting digital technologies, and investigate the current practice and possible approaches to achieve the goal. To be specific, this research has the following three objectives: (1) to explore the current digital technology implementation in the OSC industry and identify capabilities and limitations of available digital technologies utilization in OSC, (2) to identify the challenges related to digital technology implementation in OSC, (3) to present expectations of digital technology implementation from the perspective of practitioners.

2 Literature Review

Firstly, many digital technologies have been reported that could improve the quality and efficiency of the construction industry. For example, RFID could improve productivity in supply chain management and construction site monitoring (Dallasega *et al.*, 2018, Voordijk, 2019). Laser scanning could obtain thousands of points from the target buildings and create geometries with high efficiency (Lu *et al.*, 2020, Wu *et al.*, 2021). Web-based technologies can improve onsite project communication(Wang and Xue, 2008, Shirowzhan *et al.*, 2017). In addition, BIM, Internet of Things (IoT), photogrammetry, AI are all seen as promising digital technologies (Dallasega *et al.*, 2018, Voordijk, 2019). While other technologies such as augmented reality, artificial intelligence are still being enhanced and somehow influence sustainability (Zou *et al.*, 2017, Alaloul *et al.*, 2020). These technologies are presented to be able to contribute to the construction industry. However, due to the difference in construction processes, more investigations should be carried out to demonstrate if these digital technologies are applicable in OSC projects.

Secondly, for digital technology implementation in OSC, some studies are made by case studies or simulations to validate the effectiveness of specific digital technology. For example, some research tried to use technologies to automate the construction process and track the rea-time construction. To track the materials, many advanced technologies have been adopted in the off-site construction to collect the data on-site, such as bar code (Cheng and Chen, 2002), RFID, GPS (Ergen *et al.*, 2007) so on. Based on the data collection, information management systems are used to monitor the work, make decisions or give feedback, such as BIM, VR, IoT and so on (Li *et al.*, 2018, Luo *et al.*, 2020). These digital technologies could be used for geometry quality checks (Arashpour *et al.*, 2020, Guo *et al.*, 2020), supply chain management (Luo *et* *al.*, 2020), onsite assembly optimization (Chen *et al.*, 2018, Zhai *et al.*, 2019), waste management (Kabirifar *et al.*, 2020, Kabirifar *et al.*, 2021), etc. Although some digital technologies have been validated to be beneficial, there is a lack of comprehensive evaluation of digital technology implementation for OSC. How to use the available digital technologies to improve work performance remains unsolved.

Thirdly, in OSC, the design needs to consider the convenience of manufacture and assembly (Yuan *et al.*, 2018). And construction management requires more coordination between manufacture, logistics, and on-site assembly since the manufacturing and installation works are happening concurrently (Luo *et al.*, 2020). The success of onsite assembly relies on the appropriate design, accurate manufacture, and timely delivery of the prefabricated elements (Moghadam *et al.*, 2012). Despite some researches are trying to develop a framework that could integrate all the stages in one management system, it remains on the conceptual level and fail to contain all design, manufacture, transportation and installation stages (Ramaji *et al.*, 2017). In this case, the opinions from different practitioners are critical for integration and coordination on digital technology implementation. However, there is a lack of investigations that integrate opinions from all practitioners in OSC.

In summary, the research gaps can be grouped into two categories. One is technology limitation, that is if these technologies are mature enough to solve the current problems in OSC. Another is the inefficient use of technologies, which is due to the inappropriate use of the technologies or conservative attitude from the practitioners. This study will conduct an in-depth investigation in OSC, to explore the current practice, challenges and expectations of digital technology implementation from the perspective of different practitioners.

3 Research Methodology

3.1 Data collection

Semi-structured interviews were preferred to structured interviews to prevent the bias of the interviewer when asked to clarify a question (Alazzaz and Whyte, 2015, Sepasgozar *et al.*, 2018). The interview questions were designed to develop a comprehensive framework that can provide a better understanding of digital technology implementation in Chinese OSC projects. The questions were compiled based on a literature review on recent and related publications, including digital technologies (Chowdhury *et al.*, 2019, Akbarieh *et al.*, 2020), off-site construction (Jin *et al.*, 2018, Yuan *et al.*, 2020), technology adoption theory (Webster and Gardner, 2019), technology adoption in off-site construction (Wang *et al.*, 2020). Interview with open questions makes it possible that participants can explain their attitudes about the technology implementation. The criteria for selection of the qualified interviewees are mainly from two aspects: (1) Professionals working in different construction stages, including design, manufacture and on site construction in OSC, (2) With various age, professions, and experience to avoid biased interview outcomes.

The interview was carried out by face-to-face interview and took about 1 hour to 1.5 hours for each interview. It was noted that face-to-face interviews may result in more socially desirable responses and lower accuracy than computer administered questionnaires or paper-and-pencil questionnaires (Richman *et al.*, 1999). Interviews were beginning according to the provided guidance at first with open and public questions and then continued with in-depth questions. As the interview continued, more open and deep questions were asked to clarify the details of their answers. Adequate sample size is usually reached at saturation point when themes start to repeat themselves (Mason, 2010). Therefore, the completion of the interview is based on that there is no more new information after several runs of interviews. Finally, a total of 22 practitioners from different stages involved in OSC were interviewed in China. Among them, 8 are from the design stage, 8 from the manufacturing stage, 6 from the onsite construction stage.

3.2 Data analysis

The interview transcripts were made by note-taking during the interview, and further tidy-up according to the recordings. After writing the recorded interviews, the texts were reviewed by interpreters. The following step is to make a qualitative analysis of these interview data to identify the attitudes and experiences of the interviewees. Data collected from semi-structured interviews are analyzed based on thematic analysis, through the development and allocation of codes and themes. A thematic analysis was the most suitable qualitative method for analyzing interview data, as it focuses on themes and patterns to understand people's experiences, views, opinions, knowledge of things (Lamptey et al., 2020). The NVivo software is used to provide a taxonomy of technology utilisation, which could reduce manual tasks and assist in identifying tendencies, recognizing themes and deriving conclusions (Akbarieh *et al.*, 2020). The categories of thematic coding are from three aspects: current practice, challenges and expectations of digital technology implementation in OSC. There are four steps to analyze the interview data (Adetoro Adewunmi and Damilola Ajayi, 2016, Samad and Steven, 2018):

Step 1: This step is to obtain an overall picture of all transcripts. The first is to quickly browse through all interview transcripts as a whole, then make notes about the first impressions. After that, a re-read process on the transcripts is conducted one by one carefully.

Step 2: This process is called coding or indexing. The first is to label relevant phrases or sentences in the transcripts. The labels are about concepts, opinions, processes, and other relevant information about digital technologies implementation in OSC. Things that can be coded include repeated texts in multiple places, something surprising, interviewees' explicit statements on something important, something similar to a previously published literature review, and other reasons that can be regarded as relevant. This coding process aims for a conceptualization of underlying patterns.

Step 3: This step is to conceptualize the data. After conducting step 2 for all transcripts data, this step will decide which codes are the most important and create categories by bringing several codes together. The first is to go through all the codes created in the previous step, and new codes can be created by combining two or more codes. At this stage, some of the initial codes can be dropped, while the codes that are regarded as important will be kept. The second is to group the codes into different categories. The categories do not have to be of the same type, they can be about objects, processes, differences, or whatever.

Step 4: This step is to label categories and identify how they are connected. In this study, the current practice, challenges and expectations of digital technology implementation are considered for the labelling process. Then the importance of categories is analysed. It is assumed that the number of codes represents the importance of the category. The word frequency query in NVivo is selected to provide the most frequently occurring words during the matrix coding process, which could maintain analytic integrity in data analysis (Feng and Behar-Horenstein, 2019, Wilk *et al.*, 2019). These categories and their importance are the main results and will be presented in Section 4.

4 Findings and Discussion

After thematic analysis in NVivo software, all interview data are assigned to suitable categories. The proportions were used to indicate how frequently the concepts were mentioned by participants. A total of 894 quotes were collected where 175 (19.57%) were coded as current capability of digital technologies, 112 (12.53%) as technology limitations, 287 (32.10%) as challenges, 320 (35.79%) as expectations of future implementation. Detailed discussions of the results are presented below in three aspects: the capabilities and limitations of digital technologies utilization in OSC, the challenges, and the expectations for technology implementation from the perspective of practitioners.

4.1 Capabilities and limitations

12 digital technologies have been identified from the interview as well as their capability in solving construction problems, including BIM, laser scanning, photogrammetry, VR/AR, big data, RFID, robot, IoT, GPS, 3D printing, and AI. BIM is the most mentioned technology with 68 quotes (38.20%), especially in the design stage. The second and third mentioned technologies are photogrammetry with 28 quotes (15.73%) and laser scanning with 27 quotes (15.17%) both in the manufacture and onsite construction stages, where VR/AR with 12 quotes (6.74%) and big data with 11 quotes (6.18%) are also mentioned. From the perspective of professions, most of the designers mentioned BIM, while for the manufacturer and contractors, they are more focused on the 3D data collection technologies, such as photogrammetry and laser scanning, which might be helpful in real-time monitoring in their practices.

However, from the perspective of designers, BIM is still not perfect to be used in the design of OSC projects. For example, many respondents have pointed out that there is a lack of hardware or software to support a complete BIM model, in this way, it could be impossible for BIM implementation throughout the construction process currently. From the perspective of designers, compared with CAD (computer-aided design) design, it is time-consuming to design BIM models and there is a lack of automated design of DfMA (design for manufacture and assembly) method integrated with BIM software. The manufacturers claimed that some BIM models are unqualified for guiding production, which still requires many manual adjustments of the drawings. And in terms of the onsite assembly stage, there is a lack of skilled BIM engineers available in OSC projects to analyse BIM models.

Another main problem is that most technologies are still developing, and may not have mature and commercialized products in the market, which means the available technology products are still in their early stage, and cannot be directly adopted in current practice. For example, there is a lack of fair-priced and accurate VR/AR devices available in the market. The device with suitable accuracy is not available and needs to be customized with high costs. In addition, there is a need for sensors that could contribute to concrete health detection, while there is no type of sensor that could detect the inner condition of concrete structures in the market.

3D data collection methods are most mentioned by professions from the manufacture and assembly stage since they could do real-time monitoring, such as photogrammetry, laser scanning and RFID. Currently, the sensors and RFID are ready to be used for location identification of elements. They also have some limitations and need to be further improved. It is challenging to recognize materials during the manufacturing process using photogrammetry, such as rebars. The use of photogrammetry technology relies on the environment. There is the same problem for using laser scanning, such as irregular object recognition from a point cloud. Although it is easy to extract information from RFID tags, there are still many extra efforts on type selection, identification of installation position, dismantle and reuse works of RFID tags, which is inefficient to easy in real practice.

Some technologies, including big data, IoT, robots, 3D printing and AI, are less mentioned. This is because they are less introduced in the OSC industry or some of them lack the capability in solving practical problems. For example, a robot is not able to connect rebars, so that it is not utilized in a factory. And most of the interviewees have limited knowledge in 3D printing, big data, AI. These technologies need to be more investigated in OSC.

4.2 Challenges

By matrix coding and word code analysis in NVivo, the results of the nodes of professions' worries of digital technology implementation are organised in Table 1. 16 items have been identified as challenges. From the analysis of the first level of nodes, it is obvious that the two major items of threat are people's negative attitudes and the company's high expectation of technology adoption. Followed by the standardization problems in OSC. The lack of suitable organizational structure, inappropriate management strategies, economical burden on purchase of digital technologies, daily use and development of technology are also negative factors that prevent technology to be adopted in OSC successfully. In addition, some technologies might be labour-intensive and time-consuming to use compared with manual operations, especially at the early stage. Some there is a lack of skilled technology users in the construction industry. In addition, the standardization problems are also a critical issue in the current practice of OSC projects. In conclusion, there are many barriers to digital technologies adoption in OSC and the technologies need to be improved and adopted properly to meet the requirement and benefits.

Table 1. Matrix coding of challenges in NVivo

	Design			**Manufacture**			**Onsite**		**Total codes**
	SD	AT	BE	MG	TE	ME	PM	SE	
1 Company expectations of technology adoption	78	17	55	25	153	46	232	147	753
2 Complicated construction site environment	35	0	41	37	44	57	200	20	434
3 Data extraction issues	0	0	0	97	0	0	0	0	97
4 Difficulty in technology diffusion in construction industry	0	0	27	0	0	0	0	31	58
5 Digital data security issues of using technology	0	0	0	37	0	0	0	11	48
6 Economical burden on purchase, use and development of technology	87	0	67	169	83	16	69	51	542
7 Extra works required of technology adoption	0	0	25	11	36	0	0	0	72
8 Inappropriate utilization of technologies	58	0	32	0	53	0	11	0	154
9 Lack of professional technology operators in OSC industry	115	0	0	91	21	0	97	18	342
10 Lack of suitable organizational structure and management of technology adoption	57	14	80	173	89	66	29	73	581
11 Lack of supporting measures of technology adoption from government	55	0	0	0	26	0	41	0	122
12 Little value creation during whole construction life cycle	0	0	0	36	0	0	44	68	148
13 Not all collisions are detected by current BIM practice in OSC projects	26	0	13	0	0	0	33	27	99
14 People' negative attitude on technologies adoption	216	76	179	60	156	32	261	64	1044
15 Standardization problems in OSC prevent technology adoption	128	19	33	324	55	82	8	33	682
16 Time and labour consuming of adopting technology	51	0	0	47	0	0	70	0	168

Note: Structure designer=SD, Architecture=AT, BIM engineer=BE, Manager=MG, Technique engineer=TE, Machinery management engineer=ME, Project manager=PM, Site engineer=SE

4.3 Expectations

Although there are many challenges of digital technologies implementation, the practitioners in OSC expect their wide adoption can potentially improve the OSC process. The matrix coding of expectations from professions is given in Table 2. 16 items have been identified to demonstrate the needs or potential requirements of digital technologies in OSC. There is an urgent need for information delivery and exchange by using digital technologies, especially in the design stage. Many practitioners in the construction industry are willing to use technologies, which is also a great advantage of technology adoption. In addition, as different from the traditional construction industry, there is a higher expectation of achieving digitalization and informatization of OSC, especially in the manufacturing stage in the factory. These are the top three most important factors. Moreover, the stakeholders from different stages also emphasized the importance of efficiency improvement by using digital technologies.

Table 2. Matrix coding of professions and expectations factors in NVivo

	Design			**Manufacture**			**Onsite**		**Total codes**
	SD	AT	BE	MG	TE	ME	PM	SE	
1 Higher accuracy requirement than manual works	0	0	0	0	60	0	0	0	60
2 Government support on technology promotion	19	0	0	0	0	0	0	0	19
3 Shortage of labour in OSC	32	0	0	52	10	0	0	0	94
4 Need of digital data in partial processes with less data processing pressure	32	0	0	102	0	0	16	31	181
5 Need of automated design	68	49	25	23	14	0	0	0	179
6 Some technologies are available in OSC	0	0	20	32	84	0	40	16	192
7 Need of automated and efficient quality control methods	0	0	0	175	92	0	0	102	369
8 Lack of fully achieving advantages of digital technologies	135	0	37	21	0	0	9	23	225
9 Requirement of whole construction process services in OSC	327	47	26	0	10	0	0	42	452
10 Need of real-time monitoring of construction site	38	0	46	122	26	25	55	112	424
11 Need of automated production of PC	30	20	13	57	59	52	5	32	268
12 Need of guidance of construction tasks from technologies	121	37	0	190	51	0	61	29	489
13 Need of technology to improve working efficiency	54	12	17	82	174	0	152	134	625
14 Willing of realizing automation, digitalization and informalization in factory	164	0	18	92	126	0	77	296	773
15 Need of real-time information exchange and delivery	774	316	26	368	104	0	103	227	1918
16 Some people are willing to use technologies	429	41	96	167	97	28	122	44	1024

Note: Structure designer=SD, Architecture=AT, BIM engineer=BE, Manager=MG, Technique engineer=TE, Machinery management engineer=ME, Project manager=PM, Site engineer=SE

5 Conclusions

Digital technology implementation is critical for the development of OSC. Based on the in-depth interview of participants from OSC projects, opinions from different professions on digital technology implementation are analysed qualitatively. The results are summarized as follows.

It can be concluded that there are high demands for digital technologies in the OSC industry. The real-time information exchange and delivery of the whole process, automated design, construction monitoring, higher accuracy checking techniques are the major expectation from professions. In addition, specific professions presented different needs of digital technologies. For designers, they are more concerned about BIM technology, which could be integrated with automated design and DfMA. For manufacturers, they expect to realize automation, digitalization and informatization in the factory, which is mainly focused on BIM, RFID, robot, VR/AR, photogrammetry, laser scanning. While for onsite workers and project managers, their needs are more about real-time monitoring using photogrammetry, laser scanning, VR/AR, to ensure quality and efficiency of the assembly process. In conclusion, BIM, VR/AR, photogrammetry, laser scanning can be regarded as the most promising digital technologies in the OSC industry.

In another aspect, the challenges at the current stage for digital technology implementation in OSC are caused by people's negative attitude toward adopting new technologies, lack of standardization in OSC, inefficient organizational structure and management of technology implementation. Some people may not be supportive of utilizing digital technologies due to their limited knowledge. Standardization of prefabricated elements also plays a significant role in digital technology implementation. This is because if there are too many types of prefabricated elements, a higher level of digital technologies needs to be developed to accommodate them, and more associate preparations need to be carried out, therefore it leads to lower efficiency and higher cost. The higher the standardization level of OSC projects, the easier and more efficient digital technology implementation. Moreover, government and organisational strategies for using digital technologies in OSC should be established according to the identified challenges.

The current capability and limitations of digital technologies are more from a technological perspective. The way to improve the technologies capability should take their limitations into consideration. There are four types of limitations. First, technologies like RFID and sensors are quite mature and can be used directly in OSC, however reluctance from human aspects, and other management issues have prevented their wide usage. Second, some technologies are mature enough to provide adequate support to issues in OSC, however, they have not been developed to suitable commercial software packages ready to be used directly in OSC, such as BIM and VR/AR. Third, some technologies require further improvement for practical implementation. For example, automatic recognition of rebar, built-in fittings, etc. from the point clouds provided by laser scanning and photogrammetry. Forth, some technologies, such as IoT, AI, digital twin, etc. are still developing, and they are further away from practical implementation.

This study attempts to provide an overall vision on technology implementation in the current OSC industry, future research should pay more attention to how to address technologies' limitations, to meet the industry's expectations of digital technologies implementation. This study can also provide some practical guidance to government and construction organisations on how to facilitate digital technologies' development and effective utilization in OSC.

6 References

Adetoro Adewunmi, Y. & Damilola Ajayi, O., 2016. Attitudes of Nigerian facilities management professionals to the benefits of benchmarking. *Facilities,* 34**,** 468-492.

Akbarieh, A., Jayasinghe, L.B., Waldmann, D. & Teferle, F.N., 2020. BIM-based end-of-lifecycle decision making and digital deconstruction: Literature review. *Sustainability (Switzerland),* 12.

Alaloul, W.S., Liew, M.S., Zawawi, N.a.W.A. & Kennedy, I.B., 2020. Industrial Revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders. *Ain Shams Engineering Journal,* 11**,** 225-230.

Alazzaz, F. & Whyte, A., 2015. Linking employee empowerment with productivity in off-site construction. *Engineering, Construction and Architectural Management,* 22**,** 21-37.

Arashpour, M., Heidarpour, A., Akbar Nezhad, A., Hosseinifard, Z., Chileshe, N. & Hosseini, R., 2020. Performance-based control of variability and tolerance in off-site manufacture and assembly: optimization of penalty on poor production quality. *Construction Management and Economics,* 38**,** 502-514.

Arashpour, M., Kamat, V., Bai, Y., Wakefield, R. & Abbasi, B.J.a.I.C., 2018. Optimization modeling of multi-skilled resources in prefabrication: Theorizing cost analysis of process integration in off-site construction. 95**,** 1-9.

Chen, K., Xu, G., Xue, F., Zhong, R.Y., Liu, D. & Lu, W., 2018. A Physical Internet-enabled Building Information Modelling System for prefabricated construction. *International Journal of Computer Integrated Manufacturing,* 31**,** 349-361.

Cheng, M.-Y. & Chen, J.-C., 2002. Integrating barcode and GIS for monitoring construction progress. *Automation in Construction,* 11**,** 23-33.

Chowdhury, T., Adafin, J. & Wilkinson, S., 2019. Review of digital technologies to improve productivity of New Zealand construction industry. *Journal of Information Technology in Construction,* 24**,** 569-587.

Dallasega, P., Rauch, E. & Linder, C., 2018. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry,* 99**,** 205-225.

Ergen, E., Akinci, B. & Sacks, R., 2007. Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS. *Automation in Construction,* 16**,** 354-367.

Feng, X. & Behar-Horenstein, L., 2019. Maximizing NVivo utilities to analyze open-ended responses. *The Qualitative Report,* 24**,** 563-571.

Guo, J., Wang, Q. & Park, J.H., 2020. Geometric quality inspection of prefabricated MEP modules with 3D laser scanning. *Automation in Construction,* 111.

Hong, J., Shen, G.Q., Li, Z., Zhang, B. & Zhang, W., 2018. Barriers to promoting prefabricated construction in China: A cost–benefit analysis. *Journal of Cleaner Production,* 172**,** 649-660.

Jiang, R., Mao, C., Hou, L., Wu, C. & Tan, J., 2018. A SWOT analysis for promoting off-site construction under the backdrop of China's new urbanisation. *Journal of Cleaner Production,* 173**,** 225-234.

Jin, R.Y., Gao, S., Cheshmehzangi, A. & Aboagye-Nimo, E., 2018. A holistic review of off-site construction literature published between 2008 and 2018. *Journal of Cleaner Production,* 202**,** 1202-1219.

Kabirifar, K., Mojtahedi, M., Changxin Wang, C. & Tam, V.W.Y., 2021. Effective construction and demolition waste management assessment through waste management hierarchy; a case of Australian large construction companies. *Journal of Cleaner Production,* 312**,** 127790.

Kabirifar, K., Mojtahedi, M., Wang, C. & Tam, V.W.Y., 2020. Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. *Journal of Cleaner Production,* 263.

Lamptey, T., Owusu-Manu, D.G., Acheampong, A., Adesi, M. & Ghansah, F.A., 2020. A framework for the adoption of green business models in the Ghanaian construction industry. *Smart Sustainable Built Environment,* ahead-of-print.

Li, C.Z., Hong, J., Xue, F., Shen, G.Q., Xu, X. & Mok, M.K., 2016. Schedule risks in prefabrication housing production in Hong Kong: a social network analysis. *Journal of Cleaner Production,* 134**,** 482-494.

Li, C.Z., Xue, F., Li, X., Hong, J. & Shen, G.Q., 2018. An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Automation in Construction,* 89**,** 146-161.

Liu, H., Singh, G., Lu, M., Bouferguene, A. & Al-Hussein, M., 2018. BIM-based automated design and planning for boarding of light-frame residential buildings. *Automation in Construction,* 89**,** 235-249.

Lu, Q., Chen, L., Li, S. & Pitt, M., 2020. Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. *Automation in Construction,* 115.

Luo, L., Jin, X., Shen, G.Q.P., Wang, Y., Liang, X., Li, X. & Li, C.Z., 2020. Supply Chain Management for Prefabricated Building Projects in Hong Kong. *Journal of Management in Engineering,* 36.

Maskuriy, R., Selamat, A., Maresova, P., Krejcar, O. & David, O.O., 2019. Industry 4.0 for the construction industry: Review of management perspective. *Economies,* 7.

Mason, M., 2010. Sample Size and Saturation in PhD Studies Using Qualitative Interviews. *Forum Qualitative Social Research,* 11**,** 1-9.
Moghadam, M., Al-Hussein, M., Al-Jibouri, S. & Telyas, A., 2012. Post simulation visualization model for effective scheduling of modular building construction. *Canadian Journal of Civil Engineering,* 39**,** 1053-1061.
Ramaji, I.J., Memari, A.M. & Messner, J.I., 2017. Product-Oriented Information Delivery Framework for Multistory Modular Building Projects. *Journal of Computing in Civil Engineering,* 31.
Richman, W.L., Kiesler, S., Weisband, S. & Drasgow, F.J.J.O.a.P., 1999. A meta-analytic study of social desirability distortion in computer-administered questionnaires, traditional questionnaires, and interviews. 84**,** 754-775.
Samad, S. & Steven, D., 2018. Construction Technology Adoption Cube: An Investigation on Process, Factors, Barriers, Drivers and Decision Makers Using NVivo and AHP Analysis. *Buildings,* 8**,** 74-.
Sepasgozaar, S.M.E., Shirowzhan, S. & Wang, C., 2017. A Scanner Technology Acceptance Model for Construction Projects. *Procedia Engineering,* 180**,** 1237-1246.
Sepasgozar, S., Wang, C. & Shirowzhan, S., 2016a. Challenges and Opportunities for Implementation of Laser Scanners in Building Constructioned. *ISARC 2016 Proceedings of the 33rd International Symposium on Automation and Robotics in Construction*, 742-751.
Sepasgozar, S.M.E., Costin, A. & Wang, C., 2016b. Challenges of Migrating from Desktop-based BIM in Constructioned. *33th International Symposium on Automation and Robotics in Construction*, 934-942.
Sepasgozar, S.M.E., Davis, S., Loosemore, M. & Bernold, L., 2018. An investigation of modern building equipment technology adoption in the Australian construction industry. *Engineering Construction and Architectural Management,* 25**,** 1075-1091.
Shirowzhan, S., Sepasgozar, S.M.E., Zaini, I. & Wang, C., 2017. An integrated GIS and Wi-Fi based Locating system for improving construction labor communicationsed. *34th International Symposium on Automation and Robotics in Construction, ISARC 2017*International Association for Automation and Robotics in Construction I.A.A.R.C, 1052-1059.
Voordijk, J.T., 2019. Technological Mediation in Construction: Postphenomenological Inquiry into Digital Technologies. *Journal of Construction Engineering and Management,* 145.
Wang, C.C., Sepasgozar, S.M.E., Wang, M., Sun, J. & Ning, X., 2019. Green Performance Evaluation System for Energy-Efficiency-Based Planning for Construction Site Layout. *Energies,* 12**,** 4620.
Wang, C.C. & Xue, D., 2008. Using domain ontology in a semantic blogging system for construction professionals. *Tsinghua Science Technology Analysis & Strategic Management,* 13**,** 279-285.
Wang, M., Wang, C.C., Sepasgozar, S. & Zlatanova, S., 2020. A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0. *Buildings,* 10.
Webster, A. & Gardner, J., 2019. Aligning technology and institutional readiness: the adoption of innovation. *Technology Analysis & Strategic Management***,** 1-13.
Wilk, V., Soutar, G.N. & Harrigan, P., 2019. Tackling social media data analysis: Comparing and contrasting QSR NVivo and Leximancer. *Qualitative Market Research: An International Journal*.
Wu, J., Peng, L., Li, J., Zhou, X., Zhong, J., Wang, C. & Sun, J., 2021. Rapid safety monitoring and analysis of foundation pit construction using unmanned aerial vehicle images. *Automation in Construction,* 128**,** 103706.
Yin, X., Liu, H., Chen, Y. & Al-Hussein, M., 2019. Building information modelling for off-site construction: Review and future directions. *Automation in Construction,* 101**,** 72-91.
Yuan, Z., Ni, G., Wang, L., Qiao, Y., Sun, C., Xu, N. & Wang, W., 2020. Research on the barrier analysis and strength measurement of a prefabricated building design. *Sustainability (Switzerland),* 12.
Yuan, Z., Sun, C. & Wang, Y., 2018. Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Automation in Construction,* 88**,** 13-22.
Zhai, Y., Chen, K., Zhou, J.X., Cao, J., Lyu, Z., Jin, X., Shen, G.Q.P., Lu, W. & Huang, G.Q., 2019. An Internet of Things-enabled BIM platform for modular integrated construction: A case study in Hong Kong. *Advanced Engineering Informatics,* 42.
Zou, Y., Kiviniemi, A. & Jones, S.W., 2017. A review of risk management through BIM and BIM-related technologies. *Safety science,* 97**,** 88-98.