https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

Relationship between BIM implementation and Performance of OSM projects

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Abstract:

Building information modeling (BIM) and off-site manufacturing (OSM) approaches have been recognized as revolutionary methods in the construction industry. However, limited empirical studies have investigated on the relations and effects of BIM in OSM projects. Hence, this study aims to explore the direct relationship between BIM implementation and the performance of OSM projects through their key influential factors. The empirical data were collected through questionnaire surveys and analyzed using the partial least squares technique. The results show there is a strong relationship between BIM implementation and the performance of OSM projects through the integration management and cooperation behavior. Contract management plays a negative moderating effect on the relationship between integration management and the performance of OSM projects. These findings provide new insights into the detailed implementation strategies for BIM in improving OSM projects' performance through their correlated relations. This research also contributes to the effective promotion and use of BIM and OSM in construction industry.

Keywords: Building information model; Performance of off-site manufacturing; Integration management; Contract management; Partial least squares technique.

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

Introduction

The issues of low productivity and efficiency have been reported during the lifecycle of a construction project (Sawhney et al. 2014). Building information modeling (BIM) is one of the most promising recent innovations in the architecture, engineering, and construction (AEC) industry (Azhar 2011). Meanwhile, off-site manufacturing (OSM) has been confirmed as an efficient alteration to the traditional on-site construction method in the building sector (Jayasena et al. 2017). OSM enables manufacturing off-site and on-site construction to occur concurrently (Ibidapo et al. 2017). The integration of BIM and OSM has promoted mass customization in the construction sector (Huang 2007). The attributes of BIM have a significant impact on OSM implementation, which could promote an early collaboration between different OSM stakeholders and eventually enhance the productivity of the industry (Ezcan et al. 2013).

Most of the recent studies have focused on qualitative analyses of the integration of BIM and OSM for certain areas of improvement, such as the increased efficiency of construction activities through graph-based methodology (Isaac et al. 2016), improved energy consumption through operational performance (Gerrish et al. 2017), a simulation game for the improved learning process (Li et al. 2018), a framework for information delivery in modular buildings (Ramaji et al. 2017), improved visibility and traceability in prefabricated construction (Zhong et al. 2017), improved productivity from BIM-based multitrade prefabrication through a case study analysis of a complex building (Jang and Lee 2018), improved collaboration and information

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

exchange through a BIM-based interdisciplinary approach (Jin et al. 2018), the optimal assembly sequence in a concrete building (Wang et al. 2018), and a preliminary framework to integrate the last planner system with BIM and OSM (Goyal and Gao 2018). These previous studies mainly emphasized the technological aspects of the integration of BIM and OSM. A recent quantitative study has also been conducted on the identified benefit of coordination and communication from the perspective of construction organizations (Hwang et al. 2018). However, the findings seem rather unspecific for the integration of BIM and OSM. There is still a lack of empirical explorations regarding the relations and effects of BIM in improving the performance of OSM projects. In particular, an in-depth analysis is required to determine the relationship path between BIM and the performance of OSM projects from a quantitative approach.

To address the research gap and questions above, this research aims to explore the direct relationship between BIM implementation and the performance of OSM projects through their key influential factors. A questionnaire survey was adopted to collect the empirical data, which were subsequently analyzed using the partial least squares (PLS) technique. The scope of this research was based in China, as various policies have been enacted by the Chinese government for driving the use of BIM and OSM in the construction industry. For instance, in September 2016, the General Office of the State Council of China released a policy, which is to suggest the proportion of OSM use should reach at least 30% of the new buildings within 10 years (General Office of the State Council of the PRC 2016). Ultimately, the research findings would help stakeholders of OSM projects

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

to understand how BIM can affect the performance of OSM projects in detail, and subsequently formulate relevant strategies for improving the project performance. They would also help to promote the effective adoption and use of these emerging approaches of BIM and OSM in the industry.

Literature Review

Theoretical Backgrounds of BIM and OSM

The use of BIM in construction projects has been a major focus in recent years. Most of research works emphasize BIM's abilities of information sharing and data exchange. Based on these nature, BIM could address some traditional construction constrains (disintegrated approach and inefficient delivery) and change the organizational workflow in construction projects. Therefore, leveraging BIM capabilities could effectively facilitate the degree of integration and collaboration across the various disciplines from the perspective of the whole project lifecycle (Ma et al. 2018).

On the other hand, OSM can be an alternative to the traditional construction method. Scholars have explored OSM's advantages, which can increase buildability, save labor requirements, improve health and safety performance, and reduce waste, noise, and dust (Pons and Wadel 2011; Lu et al. 2012). In developed countries, this construction approach has been used frequently to improve the speed and quality of construction delivery (Nadim and Goulding 2010).

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

Successful off-site manufacturing is based on effective information exchange between supply chains. This requires efficient information management systems such as BIM. The integration of BIM and OSM could promote mass customization in the construction sector (Huang 2007). For instance, BIM is available to obtain accurate geometrical data of building components and detailed management information in an integrated data environment (CRC Construction Innovation 2007). This helps to offer a more accurate design data to manufacturers in the manufacturing process. Moreover, BIM's visual system can simulate the assembly process and conduct the complicated site and related logistics management. These attributes of BIM could promote an early integration of information from design to construction, operation, and maintenance of the OSM project (Singh et al. 2011), establish close collaborative relationships among different stakeholders working in cross-enterprise environments (Rezgui et al. 2013; Nath et al. 2015), and finally enhance the productivity of the industry.

Related Works

The related works on the integration of BIM and OSM show that this research area is still in its infancy. For instance, Nath et al. (2016) proposed that a BIM-based technologically enhanced workflow does lead to increased productivity in current off-site manufacturing industry; Liu et al. (2016) found that the key drivers of the business environment and entrepreneurial cognition can improve the technological shift toward modular prefabrication; Hwang et al. (2018) surveyed and confirmed that BIM is able to improve coordination and communication for prefabricated approaches in construction organizations in Singapore. Apart from that, many

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

technological advances have been innovated and proposed from the integration of BIM and OSM through case studies (Issac et al. 2016; Ramaji et al. 2017; Zhong et al. 2017; Jang and Lee 2018; Wang et al. 2018). Overall, the previous studies above have rendered fundamental knowledge and certain foundations for the integration of BIM and OSM. However, no prior research has investigated the interrelation between these new initiatives in depth. Hence, this study intends to fill this gap in the research by determining the relationship between BIM and OSM, particularly with respect to their implementation and key influential factors for improving the project performance.

Hypotheses development

BIM describes an object-oriented technology that revolutionizes projects' design and construction management. By employing BIM, a synthetic platform is digitally constructed to integrate key stakeholders during the lifecycle of a project (Emmitt et al. 2008; Attarzadeh et al. 2015). It has been used to manage projects from intra-firm orders toward inter-firm cooperation to enhance interoperability and effectiveness (Eadie et al. 2013). An early integration of information can be promoted from design to construction, operation, and maintenance of OSM projects (Singh et al. 2011; Goedert and Meadati 2008), which could coordinate the sequence of all activities in an appropriate manner and with well-developed logical relationships among processes (Allison 2010), and establish close collaborative relationships among different stakeholders working in cross-enterprise environments (Rezgui et al. 2013). Moreover, advanced three-dimensional (3D) design, effective collaboration, and enriched information are useful advantages of BIM to bridge OSM application gaps, which could help avoid long-winded lead-in times, high cost, and space clash (Ezcan et al. 2013). Integration management occupies an important position of project management, which refers to arranging a set of processes needed by a project orderly and economically (Demirkesen and Ozorhon 2017). Therefore, BIM implementation could provide an integration paradigm to achieve efficient management among OSM stakeholders. Thus, the following hypothesis is proposed:

H1: BIM implementation relates positively to integration management

The processes of OSM require highly continuous collaboration among all stakeholders to achieve project success. The building products are well organized, manufactured, labeled, and then delivered on time with a proper logistic arrangement to follow the building assembly process. This is in step with the theory of lean construction, which focuses on partners' mutual assistance, optimal arrangement, and integrated project management for higher productivity (Excellence Constructing 2004). The powerful function of the BIM platform can capture precise information provided for different participants and standardize the format of digital exchange for coordination and interaction with different parties across trades. The organizational integration in the project is vital, and involves experience, strategy, process, knowledge, and innovation. Therefore, it has great potential to promote the performance of OSM and enables unified organization to remain competitive (Berteaux and Javernick-Will 2015). Egan (2002) indicated that integration is conducive to team effectiveness.

Additionally, supply chain integration can develop an enriched and mature database of the OSM industry, including information of various types of OSM technology. This facilitates the exploration of partnerships and mitigation of market risks (Pan et al. 2012). Some studies stressed that flexible internal change has an important effect on better performance in the OSM projects management process (Söderlund 2010). It seems that integration management could reduce opportunistic behavior and enhance project management performance. Thus, the following hypothesis is proposed:

H2: Integration management relates positively to the performance of OSM projects.

The integration of BIM and OSM may need a new contract. Su (2013) pointed out that BIM should be used as an addendum or attachment in the existing contract system. Azhar (2011) and Chong et al. (2017) stated that it is necessary to create a new BIM legal protocol or framework covering legal issues, which could be viewed as a collateral contract to the main contract. These settings will allow participants to retain a familiar contractual framework when adopting BIM. Lee et al. (2018) proposed an integrative trust-based functional contracting model to explain how trust can improve BIM performance in EPC projects, which emphasized that BIM contracts can effectively build trust and collaboration among EPC parties and then achieve integration and contingency adaptability for project success. Chang et al. (2017) considered that a new type of contract should be signed between key project stakeholders to realize co-management and promote multilateral collaboration. Thus, contract management with respect to the BIM protocol is necessary for OSM projects. Because BIM

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

contains accurate quantities of building components and materials (Irizarry et al. 2013), and can be used to store, record and generate a series of documents (such as the volume of statistical tables, bill of materials, or schedule), which are the basis information for contract management. Utilizing BIM not only offers real-time document records and visualization capabilities but also supports multiparty integral design and collaborative teamwork. This could effectively avoid claims and improve the project integration level. Therefore, the following hypothesis is proposed:

H3: Integration management is mediated positively by contract management.

BIM offers all participants an effective communication and information exchange through the interoperable BIM components (Redmond et al. 2012). BIM is not only a simple software package but also a series of integrating processes and a platform cultivating collaborative relationships and patterns among project stakeholders (Liao and Teo 2018). Kimmance (2002) argued that there is an imperative demand for BIM technology to serve as an integral tool of information flow and workflow. This could enhance participants' flexibility in responding to requests for changes. Liu et al. (2015) designed a detailed construction schedule with a BIM-integrated function, which achieves an in-depth collaboration of BIM models with a simulated optimization scheme. Terreno et al. (2015) stated that BIM should be deployed beyond the design and construction phases of a project and the effective cooperation of BIM could result in more efficient and better-managed buildings. Therefore, BIM presents some significant changes in the traditional construction and

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delivery processes. This technology enables the integration of all stakeholders' needs on the project and the solution of problems with joint efforts, and finally promotes greater coordination efficiency and harmonious relationships among players who saw each other as opponents in the past (Azhar et al. 2008). Implementing BIM would make electronic document data become available resources for all parties and foster cooperative behavior. Therefore, the following hypothesis is proposed:

H4: BIM implementation relates positively to cooperation behavior

Cooperation is the basic condition for projects' success (Bennett and Jayes 1998). Many studies pointed out that cooperation is closely related to project performance (Chen 1998). Cooperation facilitates different organizations from different backgrounds exchanging knowledge and information frequently (Pearce 2010; Mahama 2006). Consequently, cooperative players are able to amplify their individual efforts, which finally leads to an increase in performance. Additionally, frequent information exchange is the basic element of cooperation and a key characteristic to solve problems and realize joint optimal outcomes (Cannon and Perreault 1999). Different organizations should develop adaptability to changes, which enables participants to fit in the exchange environment quickly and obtain mutual benefits, and then improve their overall performance (Heide and Miner 1992). Finally, cooperation behavior is conducive to fostering trust relationships and inspiring the diffusion of valuable knowledge and innovations, which lessens opportunism and contributes to project performance. Based on the above statements, cooperation behavior performed in OSM projects could have a

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positive impact on partnership and performance. Therefore, the following hypothesis is proposed:

H5: Cooperation behavior relates positively to performance of off-site manufacturing.

One of the functions of a contract is to minimize transaction costs. The costs accrue from opportunism and information asymmetry under an integral system. In order to avoid opportunism, a correct and matching contract should be constructed, as proper contract management will positively influence project performance (Gong et al. 2005). Therefore, when BIM is used in the OSM industry, a new contract system will be formed. Contracts have always highlighted a formal, legalistic agreement to link different organizations by business partnerships (Ferguson et al. 2005). Contract management is identified as a way to prevent ex ante and ex post risks of opportunism and secure partner investments. Signing contracts represents the specific obligation and right of conducting projects in the future. Roehrich and Lewis (2010) concluded that constructing clear and detailed contract terms could reduce uncertainties to a certain extent. Moreover, it helps to restrain opportunism through a compulsory legal effect. Luo (2002) indicated that a project contract is closely related to the interests of the company, and thus it drives stakeholders to complete tasks mutually and achieve better cooperation and performance. Dong and Chiara (2010) reported that interdependent flexibilities of contracts can equilibrate the risks between stakeholders and increase partners' outcomes in an uncertain environment. It can be explained that a certain degree of freedom within a contract structure could provide the essential "adaptability" to deal with changes (economic, technological, legal, etc.). In the OSM industry, projects are usually confronted with

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complex, inaccurate, and uncertain workflows, and flexible changes need to be supported by each stakeholder. The shared expectation of outcomes and good relationship would drive stakeholders to support each other. Based on the above perceptions, contract management is not restricted to transaction affairs, but is also used to maintain partnerships from long-term development, and finally achieve the cooperation probability. Therefore, the following hypothesis is proposed:

H6: Cooperation behavior is mediated positively by contract management

In sum, six hypotheses have been formulated and organized in a conceptual model, as illustrated in Figure 1. It consists of two major paths, namely, the technical path (H1, H2, and H3) of integration management from BIM implementation toward the performance of OSM projects and the soft or behavioral path (H4, H5, and H6) of cooperation behavior from BIM implementation toward the performance of OSM projects. Both paths are mediated by contract management. As the scope of BIM implementation in a project is determined at the outset, it is treated as the only independent and exogenous variable (represented by an oval). BIM implementation is also one of key elements of the "push model" of the performance of OSM projects.

Insert fig.1.

Research Approach

Figure 2 depicts the overall research design and flowchart. The research includes six major stages. In Stages 1 and 2, the conceptual model and six hypotheses were formulated, which were the results of the "hypotheses

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

development." In Stage 3, 26 items were identified to measure the variables. In Stage 4, an industry-wide questionnaire survey was conducted to collect the primary data. In Stage 5, the structure equation modeling (SEM)-PLS technique was used to analyze the survey data.

Insert fig.2.

A questionnaire survey approach was adopted to collect the data, and SEM was used to analyze the relationship among the variables through the PLS technique. This technique is tested by the cross-validation method of Stone (1974) and Geisser (1974) and used to detect the causal relationships and measure small data samples and skewed distributions (Hulland 2015). Therefore, the PLS method was an appropriate approach to analyze individuals' attitudes that were measured on a five-point Likert scale.

The questionnaire was designed based on the constructs in the conceptual model, and they were distributed to industry participants who are acquainted with BIM technology and OSM. Initially, the key variables are identified by a sequence of relative literature, and then the preliminary questionnaire was checked by three industry experts to confirm the clarity of the measurement items as per the context. They serve as the managing director, general manager, and senior project manager of local publicly listed companies, with an average 30 years of working experience. Then, a validity evaluation of the scale was conducted and nine items were deleted as they did not satisfy the convergent validity. Finally, the remaining 26 items were formulated as shown in Table 1. In this research, the conceptual model (Fig. 1) contains five variables, of which four are latent variables (expressed by a rectangle). As the scope of BIM implementation in a project is determined at the outset, it is

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treated as the independent and only exogenous variable (expressed by a circle). This construct relates to the extent to which BIM is applied in OSM projects. Two dimensions, BIM LOD and project phases, can be used to measure the BIM implementation. A multiplicative index provides a more reliable measure than a simple additive index for the extent to which BIM has affected a project. The level of information contained in a BIM model, and its corresponding available data, is described by the common term of "level of development" (LOD). This type of BIM maturity model had been developed by Bew and Richards (2008) and the U.K. Government Construction Client Group (2011). Furthermore, Chang et al. (2017) proposed to use BIM LOD and the project phase to reflect the BIM degree, and also provide a calculation method to capture the combined effect of the dimensions. This study used the same method to measure the construct of "BIM implementation", which is calculated by taking the multiplication of each dimension as shown in Table 2. Furthermore, all measures of the constructs were generated from the literature review and were verified by the industry experts via interviews in this research context.

Data Analysis and Findings

Data collection

The data were collected via the snowballing approach in China: sending the survey link to BIM and OSM professionals as well as distributing 40 questionnaires in person. In total, 205 sets of questionnaires were received, but only 177 of them were fully completed and valid for the data analysis. The background of the respondents spans five professions (owner, contractor, designer, manufacturer, and supervisor) with the

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proportions of 38.4%, 26%, 18.1%, 9.6%, and 7.9%, respectively. Among the 177 respondents, 35.6% have been working in their current position for 1–5 years, 34.5 % for 6–10 years, 14.7% for 11–15 years, 7.9% for 16–20 years, and 7.3% for more than 20 years. Most of the respondents were from Chinese top-50 real estate companies, architecture design institutes, prefabrication manufacture companies, and construction contractor organizations. The majority of the projects were relatively large, of mixed-type development. For example, Beijing Haidian Yongfeng City Project of Vanke (268000 m^2), New Industrial Park Service Center Project in Chengdu (90000 m^2), Chongqing prefabrication building R & D center Project (40000 m^2), Chongqing Jiangbei mouth Financial City (No.4) Project (270000 m^2), Vanke jinyu south county garden in Kunming (64900 m^2), and so on.

Moreover, the majority of projects have reached LOD 200 (31.1%) and LOD400 (27.2%) with similar proportions, meaning that a managed 3D environment has been built up using BIM, but the rate of BIM LOD500 features [e.g., four-dimensional (4D) construction sequencing, five-dimensional (5D) (cost information), and even six-dimensional (6D) (lifecycle information)] is still relatively low. As shown in Figure 3, BIM has been applied to various functions in OSM projects, and more than 50% of them have used BIM for the design and construction. Alternatively, the proportion of production and manufacturing is up to 21.3%.

Insert fig.3.

Reliability and Validity Test

A thorough measurement analysis is conducted in all constructs to reduce measurement error before implementing the hypothesis testing. The analysis includes an evaluation of the reliability and validity for this study. Generally, the internal consistency reliability is estimated through Cronbach's alpha in the research model. The value of Cronbach's alpha should be greater than 0.7 for an acceptable level of reliability (Hair et al. 2006). The validity is reflected by the composite reliability (CR) and average variance extracted (AVE). The threshold values of CR and AVE are suggested to be greater than 0.7 and 0.5, respectively (Fornell and Larcker 1981). Table 3 shows that the Cronbach's alpha values range from 0.868 to 0.899, the CR values range from 0.905 to 0.919, and the AVE values range from 0.585 to 0.656. All of them are above the required threshold values. Thus, this research demonstrates high internal consistency and convergent validity

Next, the discriminant validity should be considered, which is to distinguish the constructs. This observed dimension can be obtained from the comparison of the square root of an AVE with the absolute value of the correlative coefficients of the other latent variables. As shown in Table 4, the minimum of the square root of AVE is greater than the maximum of the absolute values of the correlative coefficients. Thus, the discriminant validity is satisfied.

Hypothesis testing

Table 5 shows the relationship between the BIM implementation and the performance of OSM projects through the six proposed hypotheses. To analyze the direct relationship between BIM and the performance of OSM projects, the two direct paths of H1, H2, H4, and H5 (Model 1) need to be analyzed first, and all results are positively significant. This means that the BIM implementation can trigger integration management ($b = 0.185$, $p < 0.01$) and cooperation behavior ($b = 0.164$, $p < 0.05$) in the OSM industry. Moreover, integration management is more effective than cooperation behavior. The hypothesized relationship between IM and POSM (H2) and that between CB and POSM (H5) are significant and positive as well ($b = 0.282$, $p < 0.01$; $b = 0.205$, $p < 0.01$). As for the moderating effect of contract management, H3 and H6 (Model 2) have been analyzed accordingly. The results show that H3 is negatively significant ($b = -0.223$, $p < 0.05$) and H6 is positively significant ($b = 0.280$, $p < 0.05$). Therefore, H3 is not accepted per the original hypothesis. This suggests that only cooperation behavior is positively mediated by contract management in improving the performance of OSM projects.

Discussions

This study has determined the relationship between BIM implementation and the performance of OSM projects through testing the proposed hypotheses. Utilizing BIM in OSM projects can effectively increase the project performance. The first contribution of this study is the discovery of a strong relationship between BIM implementation and the performance of OSM through integration management and cooperation behavior. The result is supported by the task technology fit theory. It suggests that Information Technology (IT) and

Information Communication Technology (ICT) have a positive effect on work performance (Goodhue and Thompson 1995) when the technological abilities are suitable for the demanded tasks. This effect will influence the user attitude toward deploying this technology, especially under the organization environment. From previous literature, it verified that BIM functions could be used widely in OSM projects and help to solve a series of realistic questions, such as digital manufacturing and logistics information tracking. With the background of modernization and development of construction industrialization, it is necessary to adopt new innovative technologies to effect a paradigm shift in the AEC industry. BIM and OSM have gained popularity amongst key players in the construction industry. Exploring how BIM technology affects OSM performance is meaningful and essential.

The second contribution of this research is the coordination of integration management and cooperation behavior for improving the performance of OSM projects. Despite of BIM's LOD and uses in different phases of the project, contract management affects the project stakeholders' behavior and practice in OSM projects. In which, contract management has different moderating effects on the two direct paths, which can weaken or enhance the performance of OSM projects. The weakening effect can be explained through the structure of formal contracts, which would limit the integration process to some extent. Contracts represent a legal bond and set a series of strict clauses to constrain partners' behavior and achieve self-interests (Hope and Fraser 2003), in this case, it would hurt the mutual trust, and the partnership and integration practice could be negatively affected

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

in the OSM process. This extends and clarifies the need for a clearly defined and well-connected relationship among the project stakeholders in the BIM contractual framework (Chong et al. 2017) via coordinating it through the flexible contract management in the soft or behavioral path of the SEM model. This helps to reduce the barriers during the integral process, especially the recognition of contract management as an institutional framework for rigidly governing all the transactions in the project.

Conclusion

This research has explored the relationship between BIM implementation and the performance of OSM projects through the direct technical and soft/behavioral paths. The SEM approach was adopted and analyzed using PLS to test the paths based on 177 responded questionnaires. The results show that BIM is able to improve the performance of OSM projects through its integration management and cooperation behavior. Contract management serves as a moderating effect, which can negatively affect the relationship between integration management and the performance of OSM. This research could be the first empirical study on determining the relations and effects of BIM in improving the performance of OSM projects from a quantitative approach. It extends the related body of knowledge by providing a new approach and strategy for improving the performance of OSM projects through BIM implementation. The identified relationships between BIM implementation and the performance of OSM projects are generalizable, as per the neutral sources of the literature review for its SEM constructs. The study also yields useful implications for industrial stakeholders and policy makers.

Utilizing BIM technology, construction practitioners may better carry out OSM projects. Through this study, policy makers can rethink current technological support with the focus on promoting inter-firm integration and setting up cooperative arrangements.

Certain limitations need to be considered in this study. One limitation pertains to the sample size. Although the 177 valid responses meet the requirement for the SEM-PLS analysis, a larger-sized sample may strengthen the validity of the model. Other key influential factors could be investigated, such as trust and organizational behaviors. They may play critical roles in the model, especially for the moderating effects of contract management. Furthermore, the research has not considered and calculated the actual improved performance from the BIM implementation. Although the hypotheses have been confirmed and tested for their relationships and effects of BIM in OSM projects, the direct measurement of BIM implementation towards the performance of OSM projects should be considered in future studies either through a case study approach or a rigorous simulation approach such as agent-based modelling from the key stakeholders' perspective.

Acknowledgements

The authors would like to thank the receivers and the editor for their careful evaluation and thoughtful comments. The authors express their gratitude to all the respondents who participated in this study.

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

References

Allison, H. "Reasons why project managers should champion 5D BIM software." VICO Software (10).

Attarzadeh, M., Nath, T., and Tiong, R. L. (2015). "Identifying key factors for building information modelling adoption in Singapore." *Proc., Institution of Civil Engineers-Management, Procurement and Law*, 168(5), 220–231.

Azhar, S. (2011). "Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry." *Leadership. Manag. Eng.*, 10.1061/(ASCE)LM.1943-5630.0000127, 241–252.

Azhar, S., Nadeem, A., Mok, J. Y., and Leung, B. H. (2008, August). "Building Information Modeling (BIM): A new paradigm for visual interactive modeling and simulation for construction projects." *Proc., First International Conference on Construction in Developing Countries*, Karachi, Pakistan, 435–446.

Bello, D. C., and Gilliland, D. I. (1997). "The effect of output controls, process controls, and flexibility on export channel performance." *J. Marketing*, 61(1), 22–38.

Bennett, J., and Jayes, S. J. (1998). *The Seven Pillars of Partnering: A Guide to Second Generation Partnering*, Thomas Telford, London.

Berteaux, F., and Javernick-Will, A. (2015). "Adaptation and integration for multinational project-based organizations." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000366, 31(6).

Bew, M., and Richards, M. (2008). *BIM maturity model*, Royal Institute of British Architects (RIBA) Publishing, London.

BIM Industry Working Group. (2011). "A report for the government construction client group." <http://www.bimtaskgroup.org/wp-content /uploads/2012/03/BIS-BIM-strategy-Report.pdf> (May 01, 2017)

Bryde, D., Broquetas, M., and Volm, J. M. (2013). "The project benefits of building information modelling (BIM)." *Int. J. Project Manage*., 31(7), 971–980.

Cannon, J. P., and Perreault, W. D. (1999). "Buyer-seller relationships in business markets." *J. Marketing. Res.*, 36(4), 439–460.

Chang, C. Y., Pan, W., and Howard, R. (2017). "Impact of building information modeling implementation on the acceptance of integrated delivery systems: Structural equation modeling analysis." *J. Constr. Eng. Manage.*, 143(8), 04017044.

Chen, C. C., Chen, X. P., and Meindl, J. R. (1998). "How can cooperation be fostered? The cultural effects of individualism-collectivism." *Acad. Manage. Rev.*, 23(2), 285–304.

Chong, H. Y., Fan, S. L., Sutrisna, M., Hsieh, S. H., and Tsai, C. M. (2017). "Preliminary Contractual Framework for BIM-Enabled Projects." *J. Constr. Eng. Manage.*, 143(7), 04017025.

CRC Construction Innovation. (2007). *Adopting BIM for facilities management: Solutions for managing the Sydney Opera House*, Cooperative Research Center for Construction Innovation, Brisbane, Australia.

Demirkesen, S., and Ozorhon, B. (2017). "Impact of integration management on construction project management performance." *Int. J. Project Manage.*, 35(8), 1639–1654.

Dong, F., and Chiara, N. (2010). "Improving economic efficiency of public-private partnerships for infrastructure development by contractual flexibility analysis in a highly uncertain context" *J. Struct. Financ.*, 16(1), 87.

Eadie, R., Browne, M., Odeyinka, H., McKeown, C., and McNiff, S. (2013). "BIM implementation throughout the UK construction project lifecycle: An analysis." *Autom. Constr.*, 36, 145–151.

Egan, J. (2002). *Accelerating change. A report by the Strategic Forum for Construction chaired by Sir John Egan, Rethinking Construction*, Construction Industry Council, London.

Emmitt, S., Prins, M., Otter, A. D., and Sebastian, R. (2008). “Collaborative architectural design management.” *Collaborative Architectural Design Management Tno Repository*, 103–118.

Excellence, C. (2004). *Effective teamwork: A best practice guide for the construction industry*, Constructing Excellence, Watford.

Ezcan, V., Isikdag, U., Goulding, J. (2013). “BIM and off-site manufacturing: recent research and opportunities.” *Proc., 19th CIB World Building Congress*, Brisbane, Australia.

Faerman, S. R., McCaffrey, D. P., Van Slyke, D. M. (2001) “Understanding interorganizational cooperation: public–private collaboration in regulating financial market innovation.” *Organ. Sci.* 12, 372–388.

Ferguson, R. J., Paulin, M., and Bergeron, J. (2005). “Contractual governance, relational governance, and the performance of interfirm service exchanges: The influence of boundary-spanner closeness.” *J. Acad. Mark. Sci.*, 33(2), 217–234.

Fornell, C., and Larcker, D. F. (1981). “Evaluating structural equation models with unobservable variables and measurement error.” *J. Marketing. Res.*, 39–50.

Geisser, S. (1974). “A Predictive Approach to the Random Effect Model.” *Biometrika*, 61(1), 101–107.

General Office of the State Council of the People's Republic of China. (2016). “The State Council's Guiding Opinions on vigorously developing prefabricated buildings.” <http://www.gov.cn/zhengce/content/2016-09/30/content_5114118.htm> (Sept. 14, 2018)

Gerrish, T., Ruikar, K., Cook, M., Johnson, M., Phillip, M., and Lowry, C. (2017). “BIM application to building energy performance visualisation and management: Challenges and potential.” *Energy Build.*, 144, 218–228.

Goedert, J. D., and Meadati, P. (2008). “Integrating construction process documentation into building information modeling.” *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2008)134:7(509), 134(7), 509-516.

Gong, Y., Shenkar, O., Luo, Y., and Nyaw, M. K. (2005). “Human resources and international joint venture performance: A system perspective.” *J. Int. Bus. Stud.*, 36(5), 505–518.

Goodhue, D. L., and Thompson, R. L. (1995). "Task-Technology Fit and Individual Performance." *Mis Quarterly*, 19(2), 213–236.

Goyal, M and Gao, Z. (2018). “ICCREM 2018: Innovative Technology and Intelligent Construction.” *Proc., International Conference on Construction and Real Estate Management*, 78–84.

Gu, N., and London, K. (2010). “Understanding and facilitating BIM adoption in the AEC industry.” *Autom. Constr.*, 19(8), 988–999.

Hair, J. F. J., Black, W. C., Babin, B. J., Anderson, R. E., and Tatham, R. L. (2006). *Multivariate data analysis, Vol. 6th*, Pearson Education, Inc. New Jersey, NJ.

Heide, J. B., and Miner, A. S. (1992). “The Shadow of the Future: Effects of Anticipated Interaction and Frequency of Contact on Buyer-Seller Cooperation.” *Acad. Manage. J.*, 35(2), 265–291.

Hope, J., Fraser, R. (2003). *Beyond budgeting*, Harvard Business School Press, Boston.

Huang, C., and Krawczyk, R. J. (2007). “Web-based BIM for Modular House Development Query Approach in Consumer Participatory Design.” *Proc., 3rd Int’l ASCAAD Conf.*, Embodying Virtual Architecture 559–570.

Hulland, J. (1999). “Use of partial least squares (PLS) in strategic management research: A review of four recent studies.” *Strategic. Manage. J.*, 20(2), 195–204.

Hwang, B. G., Shan, M., and Looi, K. Y. (2018). “Key Constraints and Mitigation Strategies for Prefabricated Prefinished Volumetric Construction.” *J. Clean Prod.*, 183.

Ibidapo, O., London, K., Elmualim, A., Pablo, Z., and Bayetto, P. (2017). “Exploring opportunities of integrated project delivery in off-site manufacturing of the Australian housing sector.” *Welcome to Delegates IRC 2017*, 873.

Irizarry, J., Karan, E. P., and Jalaei, F. (2013). “Integrating BIM and GIS to improve the visual monitoring of construction supply chain management.” *Autom. Constr.*, 31(5), 241–254.

Isaac, S., Bock, T., and Stoliar, Y. (2016). “A methodology for the optimal modularization of building design ☆.” *Autom. Constr.*, 65, 116–124.

Jang, S., and Lee, G. (2018). “Process, productivity, and economic analyses of BIM–based multi-trade prefabrication—A case study.” *Autom. Constr.*, 89, 86–98.

Jayasena, H. A. E. C., Yoosuff, M. Y. A. I. M., and Jayasena, H. S. (2017). “Economies of off-site concrete construction with BIM.” *7th Int. Conf., Sustainable Built Environment*, Kandy, Sri Lanka.

Jin, R., Yang, T., Piroozfar, P., Kang, B. G., Wanatowski, D., Hancock, C. M., and Tang, L. (2018. “Project-based Pedagogy in Interdisciplinary Building Design Adopting BIM.” Eng. Constr. Archi. Manage.

Kimmance, A. (2002). “An integrated Product and Process Information Modelling System for On-site Construction.” Thesis (Ph.D.). University of Loughborough, UK.

Lee, C. Y., Chong, H. Y., and Wang, X. (2018). “Enhancing BIM Performance in EPC Projects through Integrative Trust-Based Functional Contracting Model.” *J. Constr. Eng. Manage.*, 10.1061/ (ASCE) CO.19437862.0001521.

Li, X., Shen, G. Q., Wu, P., Fan, H., Wu, H., and Teng, Y. (2018). “RBL-PHP: Simulation of Lean Construction and Information Technologies for Prefabrication Housing Production.” *J. Manage. Eng.*, 10.1061/ (ASCE) ME.1943-5479.0000577, 34(2).

Liao, L., Ai Lin Teo, E. (2018). “Organizational Change Perspective on People Management in BIM Implementation in Building Projects.” *J. Manage. Eng.*, 10.1061/ (ASCE) ME.1943-5479.0000604 34(3), 04018008.

Liu, G., Li, K., Zhao, D., and Mao, C. (2016). “Business model innovation and its drivers in the Chinese construction industry during the shift to modular prefabrication.” *J. Manage. Eng.*, 10.1061/ (ASCE) ME.1943-5479.0000501 33(3), 04016051.

Liu, H., Al-Hussein, M., and Lu, M. (2015). “BIM-based integrated approach for detailed construction scheduling under resource constraints.” *Autom. Constr.*, 53, 29–43.

London, K., Pablo, Z., and Khalfan, M. (2015). “A multilevel analysis of collaboration in offsite manufacturing supply chains using actor network theory.” *Conf. of the Int. Innovative Production and Construction*, IPC2015 Organizing Committee, 117–122.

Lu, A., Ngo, T., Crawford, R. H., Gammampila, R., and Mendis, P. (2012). “Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules.” *Energ. Buildings*, 47(47), 159–168.

Lu, P., Guo, S., Qian, L., He, P., and Xu, X. (2015). “The effectiveness of contractual and relational governances in construction projects in China.” *Int. J. Project Manage.*, 33(1), 212–222.

Lui, S. S., Wong, Y. Y., Liu, W. P. (2009) “Asset specificity roles in interfirm cooperation: reducing opportunistic behavior or increasing cooperative behavior?” *J. Bus. Res.*, 62 (11), 1214–1219

Luo, Y. (2002). “Contract, Cooperation, and Performance in International Joint Ventures.” *Strategic Management Journal*, 23(10), 903–919.

Ma, X., Xiong, F., Olawumi, T. O., Dong, N., and Chan, A. P. (2018). “Conceptual Framework and Roadmap Approach for Integrating BIM into Lifecycle Project Management.” *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000647, 34(6), 05018011.

Mahama, H. (2006). “Management control systems, cooperation and performance in strategic supply relationships:

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

A survey in the mines." *Manage Accounting Res.*, 17(3), 315–339.

Nadim, W., and Goulding, J. S. (2010). "Offsite production in the UK: the way forward? A UK construction industry perspective." *Construction Innovation*, 10(2), 181–202.

Nath, T., Attarzadeh, M., and Tiong, R. L. K. (2016). "Precast workflow productivity measurement through BIM adoption." *Management Procurement & Law*, 169(5).

Nath, T., Attarzadeh, M., Tiong, R. L., Chidambaram, C., and Yu, Z. (2015). "Productivity improvement of precast shop drawings generation through BIM-based process re-engineering." *Autom. Constr.*, 54, 54–68.

Pan, W., Gibb, A. G. F., and Dainty, A. R. J. (2012). "Strategies for Integrating the Use of Off-Site Production Technologies in House Building." *J. Constr. Eng. Manage.*, 138(11), 1331–1340.

Pasquire, C. L., and Connolly, G. E. (2002). "Leaner construction through off-site manufacturing." *Proc., Tenth Annual Conf. of the Int. Group for Lean Construction (IGLC-10)*, 263–275.

Pearce, R. J. (2010). "Looking inside the joint venture to help understand the link between inter-parent cooperation and performance." *J. Manage Stud.*, 38(4), 557–582.

Pinto, J. K., Slevin, D. P., and English, B. (2009). "Trust in projects: An empirical assessment of owner/contractor relationships." *Int. J. Project Manage.*, 27(6), 638–648.

Pons, O., and Wadel, G. (2011). "Environmental impacts of prefabricated school buildings in Catalonia." *Habitat International*, 35(4), 553–563.

Ramaji, I. J., Memari, A. M., and Messner, J. I. (2017). "Product-Oriented Information Delivery Framework for Multistory Modular Building Projects." *J. Comput. Civil Eng.*, 31(4), 04017001.

Redmond, A., Hore, A., Alshawi, M., and West, R. (2012). "Exploring how information exchanges can be enhanced through Cloud BIM." *Auto. Constr.*, 4, 175–183.

Rezgui, Y., Beach, T., and Rana, O. (2013). "A governance approach for BIM management across lifecycle and supply chains using mixed-modes of information delivery." *J. Civ. Eng. Manag.*, 19(2), 239–258.

Roehrich, J. K., and Lewis, M. A. (2010). ″Towards a model of governance in complex (product–service) inter-organizational systems.″ *Constr. Manage. Econ.*, 28(11), 1155–1164.

Sawhney, A., Agnihotri, R., and Kumar Paul, V. (2014). "Grand challenges for the Indian construction industry." *Built Environ. Proj. Asset Manag.*, 4(4), 317–334.

Singh, V., Gu, N., and Wang, X. (2011). "A theoretical framework of a BIM-based multi-disciplinary collaboration platform." *Autom. Constr.*, 20(2), 134–144.

Söderlund, J. (2010). "Knowledge entrainment and project management: The case of large-scale transformation projects." *Int. J. Project Manage.*, 28(2), 130–141.

Stone, M. (1974). "Cross-Validatory Choice and Assessment of Statistical Predictions." *J. R Stat. Soc.*, 36(2), 111–147.

Su, H. (2013). "Research on Construction Contract under BIM Conditions." *J. Applied. Sci.*, 13(19), 3926–3930.

Terreno, S., Anumba, C. J., Gannon, E. Dubler, C. (2015). "The benefits of BIM integration with facilities management: A preliminary case study." *J. Comput. Civ. Eng.*, ASCE10.1061/9780784479247.084, 675–683.

Wang, Y., Yuan, Z., and Sun, C. (2018). "Research on assembly sequence planning and optimization of precast concrete buildings." *J. Civ. Eng. Manag.*, 24(2), 106–115.

Zhong, R. Y., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Ng, S. T., Lu, W., Shen, G. Q. P., and Huang, G. Q. (2017).

https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704

"Prefabricated construction enabled by the Internet-of-Things." *Automo. Constr.*, 76, 59–70.

Figure Caption List

●**Fig.1. Conceptual model between BIM implementation and performance of OSM projects**

●**Fig.2. Research design and flowchart**

●**Fig.3. Project phases assisted by BIM**

Tables

Table 1. Constructs and Items

Constructs	Items	Sources
Integration management (IM)	A1 BIM can manage project document effectively and provide access to stakeholders to download.	Singh et al. (2011) Goedert, J. D., and Meadati, P. (2008)

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	A2 Using BIM platform to exchange knowledge and information with all parties is faster and more effective.	Bryde et al. (2013)
	A3 Building information model can be effectively used to coordinate sequence of all activities in an appropriate manner and well-developed logical relationships among processes.	Allison (2010)
	A4 The application of BIM can achieve the integration of project staff into the current project processes and increase teamwork effectiveness at the project level.	Demirkesen and Ozorhon (2017) Emmitt et al. (2008)
	A5 BIM represents a new paradigm, can integrate customers, suppliers, contractors, and operators into the whole processes and development of knowledge sharing mechanisms among customers, suppliers, and project teams.	Demirkesen and Ozorhon (2017) Rezgui et al. (2013)
	A6 The team use BIM to manage and record all change requests in the project, making modifications, updates in project management plan and project documents, and integration of all changes into project deliverable.	Demirkesen and Ozorhon (2017) Egan (2002)
Cooperation behavior(CB)	B1 The interoperable BIM components underpin effective communication and information exchange between stakeholders.	Liao and Teo (2018) Redmond et al. (2012)
	B2 Flexibility in response to requests for changes is a characteristic of our relationship.	Pearce (2001) Faerman et al. (2001)
	B3 When an unexpected situation arises, the partners would rather work out a new deal	Pearce (2001) Bello and Gilliland

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	than hold each other to the original terms.	(1997)
	B4 Exchange of information in our relationship takes place frequently, informally, and openly.	Pearce (2001) Mahama (2006)
	B5 The partners keep one another informed of changes and events that might affect them.	Pearce (2001)
	B6 In most aspects of our relationship, the parties are jointly responsible for getting things done.	Pearce (2001) Cannon and Perreault (1999)
	B7 Problems are treated as joint rather than individual responsibilities in the cooperation process.	Pearce (2001) Cannon and Perreault (1999)
Contract management(CM)	C1 The contract has a clear expression of the default.	Lu et al. (2015)
	C2 The contract has specified the procedures and methods for disputes.	Lu et al. (2015)
	C3 A new type of contract should be signed between key project stakeholders to realize co-management and promote multilateral collaboration.	Azhar et al. (2008) Chang et al. (2017) Chong et al.(2017)
	C4 Our relationship with the partner is governed primarily by written contracts and agreements.	Lui et al. (2009)
	C5 We have formal agreements that detail the obligations and rights of both parties.	Azhar et al. (2008) Lui et al. (2009)
	C6 The contract has specified major principles or guidelines for handling unanticipated contingencies as they arise.	Ferguson et al. (2005) Lu et al. (2015)
	C7 The contract has allowed us to respond	Lu et al. (2014)

	quickly to match evolving client requirements.	
	C8 The contract has provided alternative solutions for potential contingencies.	Lu et al. (2014)
Performance of off-site manufacturing (POSM)	E1 This project has come in on schedule.	Pinto et al. (2009)
	E2 This project has come in on budget.	Pinto et al. (2009)
	E3 This project can realize the timeliness of components transportation.	Pasquire and Connolly (2002)
	E4 This project can achieve safe construction.	Pinto et al. (2009)
	E5 The construction quality and the deliverable quality accord with the standard.	Pinto et al. (2009)

Table 2. Measurement of Degree of BIM Implementation

BIM Level	Phases of project
LOD100: The element is represented with a generic representation	Operation and maintenance
LOD200: The element is represented with a generic object	Design

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LOD300: The element is represented as a specific object with a specific assembly	Logistics and transportation
LOD400: The element is represented as a specific object with a specific assembly and with the installation details	Construction
LOD500: The element is a field verified representation	Operation and maintenance
Normalized score = number of level/5.	Normalized score = number of phases assisted by BIM/5

Table 3. Measurement Properties

Constructs	Items	Outer Loading	Cronbach's alpha	Composite Reliability	Average Variance Extracted
IM	A1	0.714	0.885	0.913	0.636
	A2	0.835			
	A3	0.815			
	A4	0.808			
	A5	0.829			
	A6	0.776			
CB	B1	0.748	0.882	0.908	0.585
	B2	0.716			

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	B3	0.747			
	B4	0.803			
	B5	0.783			
	B6	0.787			
	B7	0.769			
CM	C1	0.803	0.899	0.919	0.587
	C2	0.796			
	C3	0.753			
	C4	0.765			
	C5	0.712			
	C6	0.780			
	C7	0.772			
	C8	0.747			
POSM	E1	0.860	0.868	0.905	0.656
	E2	0.743			
	E3	0.837			
	E4	0.803			
	E5	0.802			

Table 4. Correlations of Latent Variables and the Values of Discriminant Validity

Variables	BI	CB	CM	IM	POSM
BI	1.000				
CB	0.164	0.765			
CM	0.179	0.759	0.766		
IM	0.185	0.752	0.716	0.797	
POSM	0.236	0.664	0.677	0.694	0.810

Note: BI=BIM implementation; CB=Cooperation Behavior; CM=Contract Management; IM=Integration Management; POSM=Performance of Off-site Manufacturing.

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Table 5. Results of Hypothesis Testing

		Model 1		Model 2		
Hypothesis	Path	Coefficients	T values	Coefficients	T values	Results
H1(+)	BI⟶ IM	0.185**	2.724	0.185**	2.702	YES
H2(+)	IM⟶ POSM	0.445***	5.344	0.282**	2.814	YES
H4(-)	BI⟶ CB	0.164*	2.076	0.164*	2.117	YES
H5(+)	CB⟶POSM	0.330***	4.277	0.205**	2.581	YES
	Moderating effect					
H3(+)	IM-CM⟶ POSM			−0.223*	2.003	NO

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H6(+)	CB-CM $\rightarrow$ POSM	0.280*	2.792	YES