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EXPLORING THE LINKAGES BETWEEN THE ADOPTION OF BIM AND DESIGN ERROR REDUCTION

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ABSTRACT

Ensuring a timely, efficient and cost-effective delivery of facilities is an ongoing major concern for the construction industry. Human errors committed during the design and construction processes and omissions and design changes contribute to delays, leading to rework and cost overruns. A previous study has identified that the costs of design error related rework could add around 16% to the original contract value, and delays have exceeded the original contract duration by over 50% in some construction projects. Minimizing rework helps to improve project performance and timely delivery. Although building information modelling (BIM) is regarded as an effective technology with the potential to help reduce the amount of rework on construction projects, there is no support yet for this view from empirical evidence. Current research on rework management in construction has paid insufficient attention to the potential for improved communication and the self-consistent information flow between the project actors and a BIM database. This study scrutinizes the role of BIM in reducing the frequency of design errors, minimizing the amount of rework and enhancing the construction productivity in construction projects in China. A conceptual design error reduction (DER) model was proposed based on the advice and expertise of a total of 120 BIM and construction experts in China. Seven indicators are identified as crucial factors influencing design error. Clash detection (CD) and design coordination (DC) were found to be the two most important indicators from respondents' rating. The study advances the understanding of the extent to which BIM can be made use of to reduce the amount of design errors and help improve project performance.

Keywords: building information modelling (BIM), construction projects, design error, reduction.

1 INTRODUCTION

Information technology (IT) has gradually played a growing important role in the design of buildings and engineering facilities. The adoption of building information modelling (BIM) in building design and construction planning appears to provide competitive advantage, technological opportunity and the ability to address structural and process problems that exist [1, 2]. In general, BIM can be used for the purposes of i) visualization (e.g. 3D renderings); ii) fabrication/shop drawings generation; iii) real-time communication; iv) enhancing code reviews/checking; v) cost estimating; vi) construction sequencing; vii) conflict, interference and collision detection; and viii) forensic analysis, during the design and construction phases [3]. It has been argued that BIM significantly improves the efficiency and effectiveness of delivery processes and the constructed facility [4]. In this sense, BIM can play a pivotal role in the transferring and sharing of knowledge and information [5], which has the potential for preventing errors and reworks. However, limited research has been done in investigating the role of BIM as a means of achieving these aims. The role of these design technological solutions in helping to prevent design error and rework has not been well defined. While some studies argued that these modelling technologies help to shorten project periods and reduce design errors and the occurrence of reworks [6, 7], some other studies argued that these technological solutions carry with them increased risk of errors and reworks as each solution adds to the number of possible interventions to be made and the interactions that occur as a result [2]. That is, an over-reliance on visualization or BIM technology in design creates the

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possibility of enhanced responsibility on the part of the design professional, if the information input into the system is incorrect or the software processes it incorrectly [2, 8]. Decisions made based on data that are imprecise, incomplete or otherwise faulty can only lead to 'garbage in' [2, 9]. Decision makers then have ineffective virtual models. An unhealthy reliance on incompatible software can certainly have devastating consequences [10]. So far, there is no theoretical or empirical foundation to support the view that BIM reduces rework in construction projects. Thus, the primary objective of this paper is to provide some preliminary findings on the potential roles that BIM that could have been played in preventing these errors and reworks as well as to gather evidence of cases where BIM did help to prevent errors and reworks in construction projects.

2 LITERATURE REVIEW

BIM has been evidenced by many researchers as an effective means for facilitating design processes [11–15], reducing design error [2, 16, 17]. For example, Baoping *et al.* [17] pointed out that the implementation of BIM could effectively integrate various professional design information, and sufficiently boost the ability of sharing and re-using this information. Previous studies also demonstrated that BIM has the ability to facilitate information sharing and enhance communication among project practitioners, and furnish innovative solutions for better design [18]. BIM made it possible for all the parties participating early in the projects to simultaneously address the design information with the purpose of shortening time and reducing errors/omissions [11].

Previous studies suggested that clash detection (CD) can be the most effective means for time and cost saving by using BIM. Conflicts, which may give rise to inconsistencies and disputes of design, could be identified before the building was actually constructed, thereby facilitating coordination between designers and contractors [19]. As stated by Azhar [3], BIM technology could be primarily used as a virtual instrument to identify latent collisions or clashes among a variety of structural, mechanical, electrical and plumbing systems. Early detection via the BIM model in the design phase could be beneficial for error reductions, with consequent cost and schedule savings. In addition, CD could be an efficient way to accelerate the construction process, reduce project budgets, minimize errors and yield a better construction process [11]. Design coordination (DC) could be perceived as the major strength of implementing BIM in the early design stage by integrating and coordinating all the design systems with the goal of avoiding conflicts. A conceptual framework proposed by Wang *et al.* [20] denoted that BIM could be utilized as a practical tool for integrating facility management (FM) works into early design stages with the intention of consolidating collaboration between the design team and the FM team, thereby reducing modifications. As indicated by Eastman *et al.* [19], the application of BIM can coordinate all the design systems of a building, and synthesize them into one model.

Design consultants always ascertained that the implementation of BIM could enhance the quality of the documents by reducing human error (HE) as well as motivate architects to facilitate the building process from a virtual finalized project model in the design stage. Reduced HE could yield better ability to decrease mistakes or omissions that would give rise to design errors and hinder scheduled growth [21]. A 'bad apple' theory of HE proposed by Love *et al.* [22] was regarded as latent conditions contributing to errors. A systemic model was further developed with the aim of aiding BIM in reducing these errors. BIM can be utilized as a tool for efficiently simulating and analysing design drawing and documents with the purpose of reducing incomplete, incorrect, and remiss drawings or documents [3]. Four detailed case studies that utilized BIM were analysed by Kaner *et al.* [23], revealing certain amelioration in design quality due to error-free drawings. Sacks [24] explored that the cost of drafting could be reduced by approximately 80%–84% through the 3D parametric modelling. Another research carried out by Sacks and Barak [7] suggested that the underlying productivity gains from 3D modelling could be ranged from 15% to 41% of the time requisite for drawing outputs. Bernstein *et al.* [25] also indicated that the production cycle of design process could be substantially diminished by applying BIM in reducing document errors and omissions. Any design changes incorporated in the BIM model could be automatically updated, resulting in less rework by reducing drawing errors (DEs) and omissions [17, 20].

The successful implementation of BIM aids all project stakeholders engaged in the early design phase in the enhancement of communication and collaboration compared with the traditional processes [26]. As the diffusion of BIM implementation accelerates, collaboration among project practitioners should be promoted. A case study reviewed by Aranda-Mena *et al.* [27] implied that the implementation of BIM can increase the confidence of design processes, improve coordination between various practitioners, thus reducing rework and enhancing the functionality of design. Rajendran *et al.* [16] also stated that BIM has the ability to provide visible connections among project practitioners so as to foster design process and faster collaboration. Meanwhile, synchronized information with respect to construction time, cost and quality could be afforded in the BIM model with the aim of achieving common objectives (such as error reduction) within all participants [18, 28]. It is believed that BIM technology will substantially elevate the efficiency and effectiveness of delivery processes and the constructability of a facility [13, 17]. Bynum *et al.* [29] ascertained that the ability to apply BIM to virtually constitute a building prior to constructing the real-world building yields an operative approach to examine its constructability in the real projects and to address any indeterminacies or discrepancies during the design process. This resulted in more efficient work of advancing design process and decreasing design errors. Also, the digital and computable data could be easily utilized by project teams to enhance the constructability and practicality (CP) of construction projects [3], as well as promote cooperation and coordination of all project participants [30].

KI could be interchanged and applied among construction practitioners and site engineers to discover and alleviate problems on site and decrease the time and cost of addressing matters related to constructability [31, 32]. As ascertained by Linderoth *et al.* [15], BIM can perform a vital role of facilitating knowledge, information and expertise sharing in order to prevent design errors. Motawa and Almarshad [33] proposed an integrated knowledge-based BIM system to capture information and knowledge with the purpose of perceiving the extent to which a building is deteriorating, thus to carry out preventive or corrective measures. A corresponding system developed by Ho *et al.* [32] indicated that the BIM-based knowledge sharing management (BIMKSM) system could be an effective process for promoting knowledge sharing among construction practitioners. A study performed by Josephson and Hammarlund [34] suggested that lack of knowledge, information and motivation were generally considered to be the primary factors inducing defects due to design errors in building construction projects. Results showed that a total of 62% of design defects could be ascribed to inadequate knowledge and information.

Numerous researchers have earlier investigated the attributable factors affecting design error [2, 34–36], attempting to seek out effective strategies to prevent or mitigate design errors [10, 35, 37]. Managerial factors (e.g. adverse behaviour, ineffective coordination and integration, inferior constructability) and organizational factors (e.g. inexperienced personnel, insufficient information and knowledge sharing pattern, inadequate quality assurance) were identified to be the principal factors influencing design errors [21, 35, 36]. Prevention

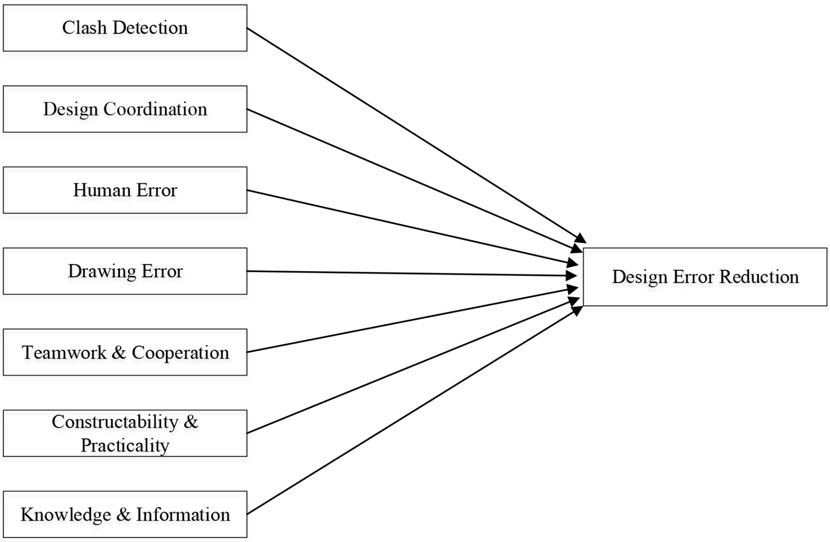

Figure 1: Conceptual framework of design error reduction model via BIM.

strategies, such as a system dynamics model, are identified by Love *et al.* [38], which can enable designers and managers to effectively manage the process of design documentation, thus ameliorating design errors. Despite these efforts, limited research has been conducted to measure the impacts of BIM implementation in reducing design error, in particular, in the construction projects in Chinese Mainland. Based on the literature review above, a conceptual model based on the different design error reduction (DER) indicators is proposed (Fig. 1). These indicators include CD, DC, human error (HE), DE, teamwork and cooperation (TC), CP, and knowledge and information sharing (KI).

3 METHODOLOGY

With the purpose of examining the conceptual model and identifying the impacts of BIM in reducing design error, a questionnaire survey was conducted as the primary means of collecting project-based data. Generally, questionnaire survey is applied to collect quantitative data scaled by respondents, and thus for statistical analysis. The advantage of using questionnaire survey is to have a large amount of quantitative data, allowing synthesizing the major findings [39]. As suggested by Bradburn *et al.* [40], the mixed data collection methods, consisting of literature review and semi-structured interviews, were employed in order to better design the survey and to acquire more accurate, valid and detailed information with respect to the respondents. In achieving this, an exploratory and thorough literature review was initially carried out to gain a preliminary understanding of the attributable factors affecting design errors through the implementation of BIM. Drawn on the information gleaned from the literature, a draft of the questionnaire survey was created in plain and clear language to strengthen the respondents' ability to make sound judgement [41], in order to collect data regarding BIM-related factors influencing design error. Then, with the purpose of yielding a balanced review of the research topic from different backgrounds, the questionnaire was sent to 14 experts in the field of BIM implementation. The aim of this pre-test process was to evaluate the appropriateness and rationality of the questionnaire, examine the scope and content, as well as identify the obscure expressions [41]. Based on the feedback from experts, the questionnaire was further modified and subsequently disseminated to targeted project-based respondents.

The questionnaire items applied to measure the impacts of BIM in reducing design errors were developed built on the information captured from the literature and experts' views. These factors were principally based on a comprehensive review of the frameworks presented by [2, 3, 17, 22, 26], as well as the outcomes of preliminary expert interviews. With the additional modification based on the feedback, a total of 7 factors were ultimately encompassed into the questionnaire (see Table 1). The overall impact of BIM implementation in reducing design error was measured on a five-point scale. Then, respondents were asked to rate the level of agreement on the importance of each separate items based on a five-point Likert scale (i.e. 1 represents 'strongly disagree' and 5 indicates 'strongly agree'), and their detailed measurement items are presented in Table 1.

This preliminary study incorporated BIM and construction experts from the Chinese Mainland. Since the implementation of BIM in China's construction industry is relatively new and slow, a completely random sampling or stratified sample would not be appropriate. The target respondents were identified by selecting the informed senior and specialized personnel directly participating in BIM-based projects. As a result, a wide variety of BIM-based projects in five cities in different geographic locations in China, including Beijing (the North), Guangzhou, Shenzhen (the South), Shanghai (the East) and Chongqing (the West), together with different project characteristics were selected to intensify the representativeness of the sample and thus yield a better view of industry practice in China.

The finalized questionnaire involves two parts. The first part was designed to collect background information regarding the respondents and projects. The second part contained rating the overall impact of BIM implementation in reducing design error and the contributory factors. The data of questionnaire survey was collected by using three means including e-mail invitation, online survey system (www.sojump.com) and personal visits. Over a period of 3 months between November 2015 to January 2016, a total of 155 questionnaires were returned from the above-mentioned cities. After excluding invalid or incomplete questionnaires, the remaining 120 valid questionnaires, representing a great response rate of 77.4%, was identified and used for subsequent analysis. After completing the questionnaires, most respondents were willing to provide further support to our study and expected to obtain the results of the questionnaires. Among the 120 valid responses, around 47% was collected through the online survey system, with the remaining 35% and 18.33% gleaned by personal

Table 1: Proposed design error reduction (DER) indicators.

Code	Items	Reference
CD	Clash detection	[3, 11, 19]
DC	Design coordination	[19, 20]
HE	Human error	[2, 21, 22, 42]
DE	Drawing error	[3, 7, 16, 19, 23, 24, 25]
TC	Teamwork and cooperation	[16, 17, 26, 27, 28]
CP	Constructability and practicality	[3, 12, 16, 29]
KI	Knowledge and information sharing	[15, 31, 32, 33, 34]

visits and e-mail invitations, respectively. Two statistical analysis, ANOVA and Chi-square test, were employed to compare the results from different sources, and no significant differences were found. The demographic information of these 120 respondents is presented in Table 2.

4 FINDINGS

Findings from a descriptive statistics analysis of responses derived from targeted respondents are presented in Table 3, showing the mean score with standard deviation of each indicator. The values in brackets in Table 3 also denote the ranking of importance ratings for each indicator. As demonstrated by Fraenkel *et al.* [43], in case of two or more indicators processing the same mean value, the one with lower standard deviation would be deemed as more influential. Therefore, the ranking of KI is much higher than that of TC with the same mean value. Of all the seven indicators, CD and DC obtained the highest mean score with a value of 4.41 and 4.29, respectively. These are followed by DE (4.17), constructability and practicability (4.03), and human error (3.92).

KI sharing, andTC, are the two least scored indicators. The aggregated impacts of BIM on DER was also measured by the same respondents via the five-scale method. Results showed a mean value of 4.03 with the standard deviation 0.81. This aggregated factor was used as the dependent variable for subsequent regression analysis. Reliability of the constructs was tested by deploying Cronbach's coefficient alpha. The alpha levels for each of the constructs were higher than the threshold of 0.70, indicating that the scales were a reliable measure to be accepted [44]. A test for internal consistency and reliability of these indicators provided a satisfactory Cronbach's coefficient alpha of 0.874. ANOVA tests were then performed to

Table 2: Demographic information of targeted respondents.

Parameter	Category	N	%	Parameter	Category	N	%
Nature of project participants	Client	25	20.83	Number[a]	1–2	83	69.17
	Designer	24	20.00		3–4	25	20.83
	Contractor	43	35.83		5–6	8	6.67
	Consultant	28	23.33		Above 6	4	3.33
Work experience	Below 2	22	18.33	Number[b]	Below 1	8	6.67
	2–5	39	32.50		1–3	67	55.83
	5–10	42	35.00		3–5	30	25.00
	10–15	12	10.00		5–7	10	8.33
	Above 15	5	4.17		Above 7	5	4.17
Education background	Below junior college	5	4.17				
	Junior college	9	7.50				
	Bachelor	65	54.17				
	Master	33	27.50				
	Doctor	8	6.67				

[a] Number of BIM-based projects involved; [b] Number of years for implementing BIM.

Table 3: Results of design error reduction (DER) indicators.

Construct	Code	Items description	Mean	SD
Clash detection	CD	Early detection of collisions via BIM substantially reduced design error and subsequent rework	4.41(1)	0.66
Design coordination	DC	Integrating and coordinating all the design systems with the goal of avoiding conflicts and enhancing collaboration	4.29(2)	0.76
Human error	HE	Human error could be reduced through the implementation of BIM	3.92(5)	0.87
Drawing error	DE	Drawing errors/omissions could be greatly ameliorated through BIM implementation	4.17(3)	0.78
Teamwork and cooperation	TC	BIM could enhance TC in the early design phase with the purpose of enhancing communication and facilitating design process	3.88(7)	0.90
Constructability & practicability	CP	BIM could substantially improve the efficiency and effectiveness of delivery processes and the constructability of a facility	4.03(4)	0.83
Knowledge & information sharing	KI	KI could be sufficiently interchanged and applied among construction practitioners, thus to discover and alleviate problems in the early design phase	3.88(6)	0.83

identify how the aggregated impacts of BIM on DER are associated with the type of project participants, respondents' work experience and project size.

The 'type of project participants' is found to be insignificantly associated with the dependent variable, indicating that the impacts of BIM on DER has no significant correlation with the type of project participants (Table 4). A similar result is also revealed in the association between respondents' work experience and the impacts of BIM on DER. Both of the results are further analysed by the ordinary least squares (OLS) regression method, which indicates the same insignificant outcomes. Although no significant different association is evidenced by an ANOVA test between the impacts of BIM on DER and project size, the result of OLS regression analysis demonstrated that the two variables are statistically negatively associated ($F = 8.059$, $p = 0.005$, $B = -0.131$). To examine the impacts of seven potential influential indicators on design error reduction, multiple regression analysis was conducted. Multiple regression analysis is used to analyse the relationship between a single dependent variable (DER) and several independent variables, including CD, DC, HE, DE, TC, CP, KI. Multicollinearity is examined by the variance inflation factors (VIF), which is an index that measures the severity of multi-collinearity among the independent variables. The rule of thumb is that a VIF greater than 10 would be problematic [45]. Standardization of the coefficient aims to find out which of the independent variables have a greater effect on the dependent variable in a multiple regression analysis when the variables are measured in different units of measurement. Regression diagnostics have been undertaken to examine the appropriateness of the assumptions made by fitting a regression model to a specific set of data. With the utilization of SPSS, it is found that the regression model is generally fitted

Table 4: Results of ANOVA tests for the aggregated impacts of BIM on DER by respondents' background.

Parameter	Category	N	Mean	SD		SS[a]	F-value	p-value
Nature of project participants	Client	25	3.76	0.83	Between groups	0.57	0.29	0.83
	Designer	24	3.96	0.86	Within groups	76.09		
	Contractor	43	3.84	0.65	Total	76.66		
	Consultant	28	3.79	0.96				
Work experience	Below 2	22	3.76	0.74	Between groups	3.64	1.43	0.23
	2–5	39	3.90	0.82	Within groups	73.03		
	5–10	42	3.58	0.79	Total	76.67		
	10–15	12	3.86	0.86				
	Above 15	5	3.92	0.71				

[a] SS = sum of squares

under the following assumptions of linearity (the relationships between the DER and the outcome variable is linear), normality (the errors is normally distributed), homoscedasticity (the errors variance is constant), and independence (the errors associated with one observation are not correlated with the errors of any other observation).

Table 5: Multiple regression analysis for DER model.

Model	Design error reduction model					
	Unstandardized coefficients		Standardized coefficients	t	p	Multi-collinearity
Independent variable	B	Standard error	β			VIF
Constant	0.255	0.276				
CD	0.506	0.600	0.433	1.759	0.001	1.866
DC	0.265	0.074	0.216	2.225	0.028	2.368
HE	-0.022	0.063	-0.021	-0.346	0.230	1.748
DE	0.245	0.064	0.239	3.813	0.000	1.883
TC	0.049	0.062	0.021	0.256	0.032	2.186
CP	0.246	0.060	0.203	1.759	0.001	1.866
KI	0.122	0.063	0.105	1.936	0.026	2.019

Note: Where clash detection = CD, design coordination = DC, human error = HE, drawing error = DE, teamwork and cooperation = TC, constructability and practicality = CP, knowledge and information sharing = KI

The results of regressions on the single dependent variable DER and the independent variables are depicted in Table 5. The largest VIF (2.368) in Table 5 was greatly below the cut-off point of 10, suggesting that multi-collinearity would not increase the standard errors of the DER model estimate. Multiple regression equations (RPE) with six determining factors are finally constructed as eqn (1). The results from the best-fit run of multiple regression analysis indicated a p-value of less than 0.05 and adjusted R^2 values exceed 0.75, which implied good-fit models. Results of the multiple regression analysis revealed that the value of adjusted R^2 was 0.752, indicating a good fit model. The Durbin-Watson value was 2.094, which meant that the residual errors were also normally distributed.

As shown in Table 5, all the six independent variables (CD, DC, DE, TC, CP and KI) are statistically significant with the dependent variable DER, except for HE. The p-value of this independent variable indicated that human error was not significantly associated with DER at the 5% level. Consequently, the regression analysis determined six significant independent variables, which are positively associated with the dependent variable DER. They are *CD (Early detection of collisions via BIM substantially reduced design error and subsequent rework), DC (Integrating and coordinating all the design systems with the goal of avoiding conflicts and enhancing collaboration), DE (Drawing errors/omissions could be greatly ameliorated through BIM implementation), TC (BIM could enhance teamwork in the early design phase with the purpose of enhancing communication and facilitating design process), CP (BIM could substantially improve the efficiency and effectiveness of delivery processes and the constructability of a facility), and KI (Knowledge and information could be sufficiently interchanged and applied among construction practitioners, thus to discover and alleviate problems in the early design phase).* Drawn on the six determining indicators, the design error reduction model was modified (and the associated valences of the standardized β weights) to demonstrate the causal relationship between the dependent and independent variables, as shown in Fig. 2. Final model coefficients are presented in Table 5. The regression equation can be expressed as:

$$\text{DER Model} = 0.255 + 0.506CD + 0.265DC + 0.245DE + 0.049TC + 0.246CP + 0.122KI \tag{1}$$

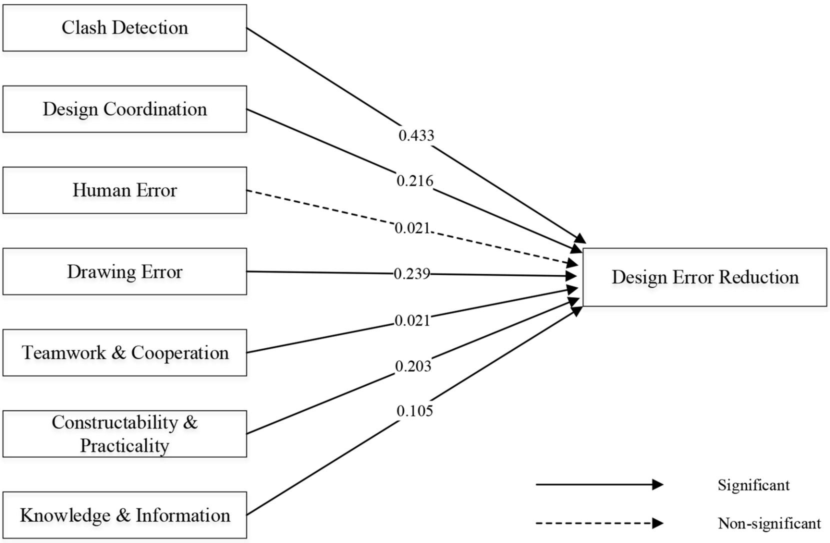

Figure 2: Revised design error reduction (DER) model.

5 DISCUSSION AND CONCLUSIONS

This study examined seven indicators that are found to be influential factors affecting design error. CD and DC were found to be the two most important indicators from respondents' rating. This corresponds with the previous investigations that BIM was frequently used as a visualization tool allowing for automatic detection of errors related to building components [2, 42]. Multiple regression analysis (OLSwas then deployed to inspect and verify the latent indicators, and a total of six determining indicators were identified. The results found that six attributable factors are statistically significant with the impacts of BIM on design error reduction, among which CD (standardized $\beta = 0.433$) has the best ability to positively affect design error reduction. CD is perceived as the most beneficial factor from the implementation of BIM in minimizing design error. Noteworthy, 'human error (HE)' was excluded from the model as suggested by the result of multiple regression analysis using OLS method. This outcome is consistent with the arguments of Reason [46] and Love *et al.* [2] that human error is an innate feature of human nature. Foord and Gulland [47] also ascertained that it is impossible to design technological systems to preclude human errors. Thus, the assertion that BIM can reduce human errors during design stage is misguided, with respect to the diverse sets of exogenous and endogenous variables affecting a designer's cognition and capability to execute tasks [10, 22].

Despite these preliminary findings, as indicated by Love *et al.* [2], BIM will considerably improve the efficiency and effectiveness of design process only by juxtaposing with other organizational and project-related strategies that have been verified. Otherwise, BIM will become a sole driver for error containment, which may give rise to the failures that would impair the performance and productivity of construction projects.

REFERENCES

[1] Dossick, C.S. & Neft, G., Organizational divisions in BIM enabled commercial construction. *Journal of Construction Engineering and Management*, **136**(4), pp. 459–467, 2010.
https://doi.org/10.1061/(ASCE)CO.1943-7862.0000109

[2] Love, P.E.D., Edwards, D.J., Han, S. & Goh, Y.M., Design error reduction: toward the effective utilization of building information modeling. In *Research in Engineering Design*, Springer-Verlag: London, 22, pp. 173–187, 2011.
https://doi.org/10.1007/s00163-011-0105-x

[3] Azhar, S., Building Information Modeling (BIM): Trends, benefits, risks and challenges for the AEC industry. *ASCE Journal of Leadership and Management in Engineering*, **11**(3), pp. 241–252, 2011.
https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

[4] Bernstein, P.G. & Taylor, J.E., Paradigm trajectories of building information modeling in project networks. *ASCE Journal of Management in Engineering*, **25**(2), pp. 69–76, 2009.
https://doi.org/10.1061/(ASCE)0742-597X(2009)25:2(69)

[5] Ho, S.-P., Tserng, H.-P. & Jan, S-H., Enhancing knowledge sharing management using BIM technology in construction. *The Scientific World Journal*, p. 10, 2013.
https://doi.org/10.1155/2013/170498

[6] Al Hattab, M. & Hamzeh, F., Using social network theory and simulation to compare traditional versus BIM-lean practice for design error management. *Automation in Construction*, **52**, pp. 59–69, 2015.
https://doi.org/10.1016/j.autcon.2015.02.014

[7] Sacks, R. & Barak, R., Impact of three-dimensional parametric modeling of buildings on productivity in structural engineering practice. *Automation in Construction*, **17**(4), pp. 439–449, 2008.
https://doi.org/10.1016/j.autcon.2007.08.003

[8] Collins, M.P., Vecchio, F.J., Selby, R.G. & Gupta, P.R., Failure of an offshore platform. *Canadian Consulting Engineer*, pp. 43–48, 2000.

[9] Brooks, D.T., Becker, B. & Marlatt, J.R., Computer applications in particular industries: securities. In *Computers and the Law, American Bar Association, Section of Science and Technology*, 3rd edn., 1981.

[10] Busby, J.S., Error and distributed cognition in design. *Design Studies*, **22**, pp. 233–254, 2001.
https://doi.org/10.1016/S0142-694X(00)00028-4

[11] Eastman, C., Teicholz, P., Sacks, R. & Liston, K., *BIM Handbook a Guide to BIM for Owners, Managers, Architects, Engineers, Contractors, and Fabricators*, John Wiley and Sons: Hoboken, NJ, 2015.

[12] Sacks, R., Radosavljevic, M. & Barak, R., Requirements for BIM based lean production management systems for construction. *Automation in Construction*, **19**, pp. 641–655, 2010.
https://doi.org/10.1016/j.autcon.2010.02.010

[13] Sacks, R., Koskela, L., Dave, B.A. & Owen, R., Interaction of lean and BIM in construction. *Journal of Construction Engineering and Management*, **136**, pp. 968–980, 2010.
https://doi.org/10.1061/(ASCE)CO.1943-7862.0000203

[14] Taylor, J.E. & Bernstein, P.G., Paradigm trajectories of BIM practice in project networks. *Journal of Management in Engineering*, **25**, pp. 69–76, 2009.
https://doi.org/10.1061/(ASCE)0742-597X(2009)25:2(69)

[15] Linderoth, H., Johansson, P. & Granath, K., The role of BIM in preventing design errors. In *30th Annual ARCOM Conference*, 1–3 September 2014, Portsmouth, pp. 703–712, 2014.

[16] Rajendran, P., Seow, T.W. & Goh, K.C., BIM in design stage to assist in time, cost and quality in construction innovation. In *1st FPTP Postgraduate Seminar 2013, 23 December 2013*, Fakulti Pengurusan Teknologi dan Perniagaan, UTHM, 2013.

[17] Baoping, C., Wei, W. & Xin, H., A research on construction project based on BIM. *E-Product E-Service and E-Entertainment (ICEEE), 2010 International Conference on, 2010. IEEE*, pp. 1–5, 2010.

[18] Fan, S.L., Skibniewski, M.J. & Hung, T.W., Effects of BIM during construction. *Journal of Applied Science and Engineering*, **17**, pp. 157–166, 2014.

[19] Eastman, C, Teicholz, P., Sacks, R. & Liston, K., *BIM Handbook: a Guide to BIM for Owners, Managers, Designers, Engineers and Contractors*, 2nd edn., John Wiley and Sons: New York, 2011.

[20] Wang, Y., Wang, X., Wang, J., Yung, P. & Jun, G., Engagement of facilities management in design stage through BIM: framework and a case study. *Advances in Civil Engineering*, pp. 1–8, 2013.
https://doi.org/10.1155/2013/189105

[21] Love, P., Lopez, R., Goh, Y.M. & Davis, P., Systemic modelling of design error causation in social infrastructure projects. *Procedia Engineering*, **14**, pp. 161–168, 2011.
https://doi.org/10.1016/j.proeng.2011.07.019

[22] Love, P., Edwards, D. J. & Han, S., Bad apple theory of human error and BIM: A systemic model for BIM implementation. *A Paper Presented at the 2011 Proceedings of the 28th ISARC*, Seoul, Korea. 2011.

[23] Kaner, I., Sacks, R., Kassian, W. & Quitt, T., Case studies of BIM adoption for precast concrete design by mid-sized structural engineering firms. *ITcon*, 2008.

[24] Sacks, R., Evaluation of economic impact of three-dimensional modeling in precast concrete engineering. *Journal of Computing in Civil Engineering*, **18**, pp. 301–312, 2004. https://doi.org/10.1061/(ASCE)0887-3801(2004)18:4(301)

[25] Bernstein, H.M., Jones, S.A., Russo, M., Laquidara-Carr, D., Taylor, W., Ramos, J., Healy, M., Lorenz, A., Fujishima, H. & Fitch, E., *The business value of BIM in North America*. Bedford: McGraw-Hill, 2012.

[26] Azhar, S., Khalfan, M. & Maqsood, T., BIM: now and beyond. *Australasian Journal of Construction Economics and Building*, pp. 12–15, 2012.

[27] Aranda-Mena, G., Crawford, J., Chevez, A. & Froese, T., BIM demystified: does it make business sense to adopt BIM? *International Journal of Managing Projects in Business*, **2**, pp. 419–434, 2009. https://doi.org/10.1108/17538370910971063

[28] Wu, W. & Issa, R., Integrated process mapping for BIM implemenation in green building project delivery. In *13th International Conference on Construction Applications of Virtual Reality (CONVR 2013)*, 2013.

[29] Bynum, P., Issa, R.R.A. & Olbina, S., BIM in support of sustainable design and construction. *Journal of Construction Engineering and Management*, **139**, pp. 24–34, 2013. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000560

[30] Rajendran, P., Seow, T. & Goh, K.C., Application of BIM for managing sustainable construction. In *International Conference of Technology Management, Business and Entrepreneurship 2012*, 18–19 December 2012, Melaka, Malaysia, 2012.

[31] Benjaoran, V. & Bhokha, S., Enhancing visualization of 4D CAD model compared to conventional methods. *Engineering, Construction and Architectural Management*, **16**, pp. 392–408, 2009. https://doi.org/10.1108/09699980910970860

[32] Ho, S.-P., Tserng, H.-P., & Jan, S.-H., Enhancing knowledge sharing management using BIM technology in construction. *The Scientific World Journal,* pp. 1–10, 2013. https://doi.org/10.1155/2013/170498

[33] Motawa, I. & Almarshad, A., A knowledge-based BIM system for building maintenance. *Automation in Construction*, **29**, pp. 173–182, 2013. https://doi.org/10.1016/j.autcon.2012.09.008

[34] Josephson, P.E. & Hammarlund, Y. (1999). The causes and costs of defects in construction: A study of seven building projects. *Automation in Construction*, **8**, pp. 681–687, 1999. https://doi.org/10.1016/S0926-5805(98)00114-9

[35] Love, P.E., Lopez, R., Kim, J.T. & Kim, M.J., Influence of organizational and project practices on design error costs. *Journal of Performance of Constructed Facilities*, **28**, pp. 303–310, 2012. https://doi.org/10.1016/S0926-5805(98)00114-9

[36] Lopez, R., Love, P.E., Edwards, D.J. & Davis, P.R., Design error classification, causation, and prevention in construction engineering. *Journal of Performance of Constructed Facilities*, **24**, pp. 399–408, 2010. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000116

[37] Love, P.E., Edwards, D.J. & Irani, Z., Forensic project management: An exploratory examination of the causal behavior of design-induced rework. *IEEE Transactions on Engineering Management*, **55**, pp. 234–247, 2008. https://doi.org/10.1109/TEM.2008.919677

[38] Love, P.E., Mandal, P., Smith, J. & Li, H., Modelling the dynamics of design error induced rework in construction. *Construction Management & Economics*, **18**, 567–574, 2000. https://doi.org/10.1080/014461900407374

[39] Creswell, J.W., *Research design: qualitative, quantitative, and mixed methods approaches*, Sage publications, 2013.

[40] Bradburn, N.M., Sudman, S., Blair, E., Locander, W., Miles, C., Singer, E. & Stocking, C., *Improving interview method and questionnaire design: Response effects to threatening Questions in Survey Research*, University Microfilms, 1992.

[41] Aibinu, A. & Jagboro, G., The effects of construction delays on project delivery in Nigerian construction industry. *International Journal of Project Management*, **20**, pp. 593–599, 2002. https://doi.org/10.1016/S0263-7863(02)00028-5

[42] Lee, H.W., Oh, H., Kim, Y. & Choi, K., Quantitative analysis of warnings in BIM. *Automation in Construction*, **51**, pp. 23–31, 2015. https://doi.org/10.1016/j.autcon.2014.12.007

[43] Fraenkel, J.R., Wallen, N.E. & Hyun, H.H., *How to design and evaluate research in education*, McGraw-Hill New York, 1993.

[44] Cronbach, L.J., Coefficient alpha and the internal structure of tests. *Psychometrika*, **16**, pp. 297–334, 1951. https://doi.org/10.1007/BF02310555

[45] Kutner, M.H., Nachtsheim, C. & Neter, J., *Applied linear regression models*, McGraw-Hill/Irwin, 2004.

[46] Reason, J., Human error: models and management. *Western Journal of Medicine; San Francisco*, **172**, pp. 393–396, 2000.

[47] Foord, A. & Gulland, W., Can technology eliminate human error? *Process Safety and Environmental Protection*, **84**, pp. 171–173, 2006. https://doi.org/10.1205/psep.05208