System dynamics modelling for BIM adoption in Thai architectural and engineering design industry

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Received 25 March 2016
Revised 31 August 2016
18 January 2017
4 March 2017
Accepted 5 April 2017

Abstract

Purpose – The causal relationships between factors related to building information modelling (BIM) adoption in the Thai architectural and engineering design industry are presented. A model is proposed to explain and forecast the adoption behaviours in the industry. This paper aims to define and compare policies for the adoption of BIM using a company case study.

Design/methodology/approach – The system dynamics (SD) approach was used. Four companies were selected as case studies for formulating a causal loop diagram. One of the companies was chosen for collecting the quantitative data for the SD model simulation during a ten-month study period. Tests of model validation were conducted for confirmation of, and confidence in, the model.

Findings – An SD model was formulated for studying BIM adoption. Four policies of BIM adoption were defined to compare with the normal operating business for the company and used as the case study. The quantitative outputs of the SD model revealed that BIM training was the best choice to optimise company performance.

Research limitations/implications – The case studies comprised architectural and engineering design companies in Thailand; therefore, the findings may not be generalisable to other Thai construction organisations or to other countries.

Practical implications – The methodology and findings can be used as guidelines for other organisations or countries that are considering BIM adoption to improve their operations.

Originality/value – The paper highlights the optimum policy for BIM adoption to achieve efficient and effective implementation.

Keywords Adoption, BIM, System dynamics, Architectural and engineering design, Building information modelling, SD model

Paper type Research paper

Introduction

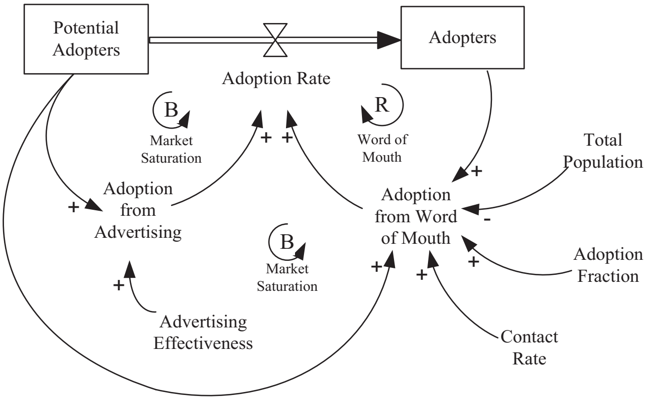
Building information modelling (BIM) is defined as a process supported by computer-generated modelling technology used in collaboration to populate information and simulate the planning, design, construction and operation of a facility (CIDB Malaysia, 2013). BIM has been described as an emerging technological and procedural shift within the architecture, engineering, construction and operations industries (Succar, 2009; Wang and Chong, 2015). BIM adopts the use of graphical relationships between structural elements in a single design, where information enables the automatic generation of drawings and reports, design analysis, schedule simulation and facilities management aimed at building an improved team with better-informed decisions in the design-build operations throughout the building lifecycle. BIM goes beyond simple drafting by modelling the relationships between structural elements in a single design with time and cost evaluations; it has been showcased as a catalyst for change (Bernstein, 2005), aimed at reducing fragmentation in the industry,

Construction Innovation
Vol. 17 No. 4, 2017
pp. 457-474
© Emerald Publishing Limited
1471-4175
DOI 10.1108/CI-03-2016-0018

improving its efficiency and effectiveness (Hampson and Bradon, 2004) and lowering the high cost of inadequate interoperability (Gallaher *et al.*, 2004). Furthermore, Son *et al.* (2015) emphasised that the benefits of BIM have not yet been fully realised during the course of implementation. Globally, there is growing pressure on designers to continue challenging the boundaries of building construction in the current climate of international competition for work (Panuwatwanich *et al.*, 2008; Steele and Murray, 2009). In affirmation, Linderoth (2010) stated "it is well-known that the number and variety of design and construction stakeholders involved in building projects can make effective and efficient collaboration difficult". Rowlinson (2017) recommended that collaborative work, information exchange and trust are factors for the development of BIM and integrated project delivery within certain organisations. These assertions suggest that the original outcome of BIM deployment may be redefined and reinterpreted.

BIM is increasingly used in numerous countries as an emerging technology and innovation to assist in the conception, design, construction and operation of building facilities (Wong *et al.*, 2011; Succar and Kassem, 2015). Previous studies have examined major issues related to BIM adoption and categorised them into management support, technical support and the compatibility of BIM, as well as software/computer skills and organisational culture (Gu and London, 2010; Son *et al.*, 2015). Thus, the application of BIM within the architectural, engineering and construction (AEC) industry has had a tremendous influence on pertinent technologies and management pedagogies towards building effective and optimal parameters to fulfil project requirements. Thailand has adopted the changing design technology of BIM for use in the Thai architectural and engineering design industry. However, the current lack of executives with appropriate knowledge and understanding is a bottleneck for BIM adoption. Therefore, this study aimed to establish a system dynamics model for BIM adoption in the Thai architectural and engineering design industry as well as to formulate policies and appropriate strategies for BIM adoption within the country. This will assist interested executives, design managers, architects and engineers to understand and assess the current status of their preparation for BIM technology.

In the area of innovation diffusion, a model was proposed and developed by Frank M. Bass in 1969 called the "Bass diffusion model" (Figure 1). This model has been widely used in forecasting new product sales and growth, marketing strategy and technology trends (Sterman, 2000; Bass, 2004; Peres *et al.*, 2010; Rao and Kishore, 2010).



Source: Adapted from Sterman (2000)

Figure 1.
The Bass diffusion model

The Bass diffusion model (Bass, 1969) has two key drivers for the diffusion of an innovation adoption in a social community including:

1. advertising (mass media); and
2. word-of-mouth behaviour of people in the community.

The Bass diffusion model was selected for the development of a system dynamics model for BIM adoption in Thailand. It was used as the guideline because the model has major elements (potential adopters, adopters and adoption rate) that are consistent with BIM adoption in the architectural and engineering design industry which is the main focus of study. A review of the literature offers an overview of existing studies. The method applied for the development of a system dynamics model is presented and validated by the findings and conclusions.

The system dynamics model and its application

System dynamics (SD) is a simulation-based approach for studying and understanding the nonlinear behaviour of large-scale and complex systems (Labi, 2014). An SD model is analysed over time using stocks, flows, internal feedback loops and time delays (Brailsford *et al.*, 2014; Labi, 2014). The SD model deals with dynamic systems comprising multiple nonlinear feedback loops linked together, reflecting the interaction and modelling of the complexity of a real-world system (Coyle, 1996). The study of the SD model begins with assessment of the whole and moves on to the relationships between the system and unit, unit and unit, and system and environment, to investigate the nature of behaviour of feedback loops and to further construct the structure of the whole to understand the relationship among the units (Brailsford *et al.*, 2014; Forrester, 1961). The SD model can be expressed in the form of a mathematical equation showing the relation of variables and the structure of the system based on the policy (Brailsford *et al.*, 2014). The model can transform the knowledge from a mental model of the respondents to the form of a stock-flow diagram and eventually to mathematical equations (Brailsford *et al.*, 2014) The SD provides an alternative solution for modelling the complex, nonlinear and multiple feedback loops of real-world problems and alleviates the deficiencies that normally occur with other modelling approaches. The important features of SD that enable these problems to be solved have been discussed in the literature (Mayo and Wichmann, 2003). Such major features include the causal loop diagram, the positive link and the negative link.

Following Forrester (1969), the cause-effect relationships of the SD are displayed in the form of a "causal loop diagram" (sometimes called a feedback structure). Identifying the cause-effect relationships and the underlying factors that drive behaviour are the first procedures to undertake when modelling by SD. The causal loop diagram consists of a set of nodes and arrows (Labi, 2014). Nodes represent the variables, and arrows are the links that demonstrate a connection or a relation between two variables as positive or negative links (Brailsford *et al.*, 2014). A "positive link" between two variables implies movement in which they tend to move in the same direction, whereas a "negative link" implies movement in the opposite direction. SD can be considered as the investigation into the information-feedback characteristics of systems. It adopts a computer-aided approach to policy analysis and design in addressing complex social, managerial, economic or ecological systems characterised by interdependence, mutual interaction, information feedback and circular causality (Sterman, 2000). The essence of SD is to learn and understand how various factors or variables may influence a system and the use of models for the design of improved organisational form and guiding policy (Forrester, 1971).

The lack of conventional project management techniques and tools has led many researchers to search for an alternative technique. The SD model has been proven as a suitable methodology for alleviating the problems of modelling complex systems in construction projects (Shen *et al*., 2005; Nguyen and Ogunlana, 2005). The SD approach is mostly applicable to a system consisting of a closed feedback structure and a nonlinear time-delayed system. This approach is aligned with the architectural and engineering design industry objective, which is extremely complex and highly dynamic (Torbett, 2003). The management functions in the industry include customer satisfaction, design quality management, human resource management and financial management. These components also involve multiple feedback and nonlinear relationships requiring both soft and hard data. Although an SD framework is focused on systems thinking, it also considers phases of constructing and testing a computer simulation characterised by a complex system and changes in system behaviour over time coupled with a loop feedback system. Studies by Sterman (2000) and Zhao *et al.* (2011) listed the below-mentioned steps to create an SD model:

- problem articulation;
- dynamic hypothesis;
- formulation;
- testing; and
- policy and formulation.

The important roles in developing an SD model according to Suryani *et al.* (2010) include:

- the system structure that will characterise its behaviour;
- the nature of the structure where the mental model plays an important role in the dynamic behaviour of the system; and
- the significant change can be used to alter the structure.

The application of SD in construction management research is not a new correct. Love *et al.* (2000) and Ogunlana *et al.* (1998) presented SD models covering the areas of design management and rework in construction. Furthermore, causal loop diagrams were used to identify factors that influenced rework in construction (Love *et al*., 1999). Love *et al.* (1999), Love *et al.* (2000) and Ogunlana *et al.* (1998) further revealed that reworks were predominantly attributable to designer errors, design changes and construction errors. Chritamara *et al.* (2002) proposed a generic system dynamics model that incorporated major sub-systems and their relationships in design-build construction projects. This model presented a better understanding of the relationships between design, procurement and construction. Le and Law (2009) developed an SD model to simulate experience transfer scenarios in a construction and property management organisation. The model was used to evaluate potential benefits and establish processes to improve knowledge transfer and learning in an architectural, engineering and construction organisation. Previous simulations of different scenarios showed that this methodology was adopted for unravelling complex learning systems.

Development of a system dynamics model for BIM adoption

There are many researches related to BIM implementation and adoption (Yalcinkaya and Singh, 2015). The adoption of BIM requires a high level of integration into existing system practices with clear focus and norms targeted at meeting the needs of both the project and the client (Rowlinson, 2017; Succar and Kassem, 2015). Gu and London (2010) grouped factors affecting the adoption of BIM into two main areas, namely:

1. technical tool functional requirements and needs; and
2. non-technical strategic issues.

Key decisions must be agreed upon and customised to facilitate the adoption of the modifying framework as individual organisations and projects have diverse goals and interests. Gu and London (2010) described four key parts that constituted a viable framework as:

1. defining the scope, purpose, roles, relationships and phases;
2. developing a work process roadmap;
3. identifying the technical requirements of BIM; and
4. customisation of the framework and the evaluation of skills, knowledge and capabilities.

Takim *et al.* (2013) noted that BIM is recognised in the AEC industry as a new management technology capable of providing an integrative solution for operating a business, while improving client satisfaction with respect to the time, cost, safety, quality and functionality of construction projects. They also identified key determining factors and implementation gaps for BIM in the industry. Further analysis of BIM adoption in the AEC industry by Gu and London (2010) addressed its availability in Australia with respect to products, processes and people. They suggested the possibility of varying levels of adoption and the need for a specific tool to facilitate BIM adoption. Research by Takim *et al.* (2013) and Gu and London (2010) are relevant to this study. However, this study outlines concrete proposals for the adoption of BIM in Thailand in line with the four perspectives of the balanced scorecard concept (Kaplan and Norton, 1996) as financial, customer, internal business processes and organisational capacity. For other countries, Ahuja *et al.* (2016) found that BIM adoption by architectural firms in India faced a slow adoption rate and was influenced by expertise, trialability and management support. In Malaysia, the main barriers to BIM adoption in engineering consulting firms are the lack of well-trained personnel, guidance and governmental support (Rogers *et al.*, 2015). In China, the key factors for BIM adoption by architects include motivation, technical defects of BIM and BIM capability (Ding *et al.*, 2015). Presently, BIM is being adopted for the implementation of design projects by Thai architectural and engineering design firms. However, no formal studies exist regarding BIM adoption in Thailand. This study is the first to offer suggestions in this area. The development of the SD model presented here is classified as follows:

Data collection

The objective was to develop a dynamic model by conducting an empirical study using the system dynamics approach to capture the dynamic behaviours of BIM adoption in Thai architectural and engineering design firms. Four Thai architectural and engineering design companies were selected as case studies from the top-ten-listed architectural and engineering design firms in the Association of Siamese Architects under Royal Patronage in Thailand. Criteria for selection included:

- original Thai companies based in Thailand;
- more than one year of BIM adoption in their design operation; and
- a trend to increase BIM adoption.

One of the companies was chosen for the collection of quantitative data during the ten-month study period. The data were used to formulate the governing equations in the SD model.

Causal loop diagram

A causal loop diagram consists of a set of variables and their causal relationships shown as links with arrows (Labi, 2014). The formulation of the causal loop diagram was initiated by setting a dynamic hypothesis (DH) that awareness of BIM leads to increase in BIM adoption in a Thai architectural and engineering design company. Increase in adoption also results in a further increase in awareness (Figure 2).

Once the DH had been set, the next step was to search for the related variables in existing theories and literature such as the diffusion of the innovation model and the variables determining the rate of adoption of the innovation model (Rogers, 2003). The determinants of customer responses to an innovation model (Sorescu *et al.*, 2003) and the Bass diffusion model (Sterman, 2000) were examined as a guideline. A draft causal diagram was then created. The diagram was validated and confirmed by experts and senior staff members at the four companies to examine and improve the variables and their relationships. Two experts from each company (i.e. eight in total) discussed the diagram in the light of their companies' operations and the draft diagram was expanded from the DH diagram (Figure 2) to create the causal loop diagram (Figure 3). This shows the cause and effect relationships between the variables that explain the behaviours of BIM adoption in the Thai architectural and engineering design case study. Some of the relationships were supported by the reviewed literature. For example, "usefulness", "ease of use" and "trialability" have effects on increasing BIM adoption (Rogers, 2003), "BIM vendor marketing effort" has indirect effects on positive BIM adoption though "BIM training" and "trialability" (Sorescu *et al.*, 2003) and "rework" has a negative effect on "design quality" and "design productivity". The arrows indicate the causal connection between pairs of variables, either with a positive (+) or negative (−) sign to indicate the direction of the change. Small parallel lines denote delays in the variable's response. Figure 3 consists of seven causal loops, two reinforcing loops or positive feedbacks (denoted by R1 and R^2) and five balancing loops or negative feedbacks (denoted by B1, B2, B3, B4 and B5). Each of these loops is described below.

Loop R1 indicates that BIM adoption leads to reduction in rework. Conversely, low rework increases design productivity and leads to higher workload completion. If the workload completion rate increases, this leads to increased company income and also company budget for BIM adoption.

Low BIM adoption increases BIM awareness amongst management teams in the companies. Increase awareness also supports greater BIM adoption (loop B1). BIM adoption leads to reduced rework with higher design quality, greater customer satisfaction and increased workload. This then results in reduced project participation for new projects and

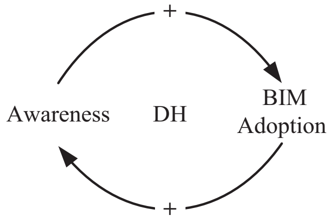


Figure 2.
Dynamic hypothesis

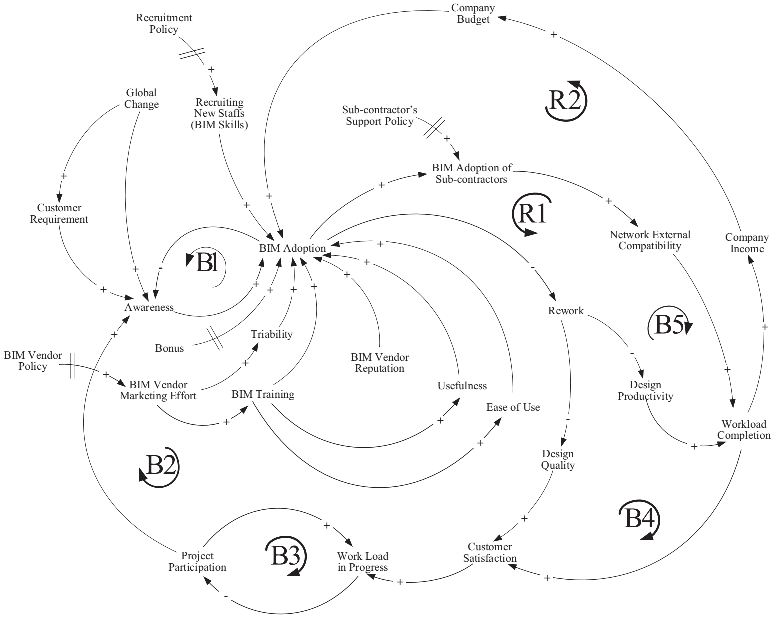


Figure 3. Causal loop diagram of BIM adoption in Thai architectural and engineering design firms

consequently greater awareness amongst the management team (loop B2). More workload in progress leads to reduced project participation with reduced workload (loop B3). Greater BIM adoption leads to reduced rework which also increases the design productivity. High design productivity then leads to higher workload completion which results in increased customer satisfaction. Customer satisfaction then leads to greater workload. Higher workload in progress results in reduced project participation and reduces BIM awareness and adoption (loop B4). One factor influencing BIM adoption is company recruitment policy (exogenous factor) for new staff members with BIM skills. BIM training has a positive influence on BIM adoption.

Another exogenous factor which has an influence on BIM adoption is BIM vendor policy. BIM vendors have increased their marketing efforts through trialability or BIM training for their customers (the companies) and this leads to increased BIM adoption by the companies. Moreover, an exogenous factor in advancing BIM adoption is BIM vendor reputation. A vendor with good reputation will influence further BIM adoption by the companies. Another exogenous factor which has an influence on BIM adoption of design sub-contractors is the sub-contractors the support policy. BIM adoption of design sub-contractors by the company leads to increased network external compatibility between the companies and the design sub-contractor as they use the same BIM software and the work files are compatible. This situation supports higher workload completion rate and also leads to increased income and budget for BIM adoption (loop R^2). Similarly, high workload completion rate generates customer satisfaction and leads to increased workload. When companies have more work in progress, they reduce new project participation which decreases awareness and BIM adoption (loop B5). Global change is an exogenous factor which drives awareness and customer requirements for BIM in the Thai architectural and engineering design industry. BIM adoption will increase through perceptions of the benefits such as reducing reworks, higher design quality and increased design productivity. These benefits satisfy customer needs and result in greater workloads. The loops (R1, R^2, B1, B2, B3, B4 and B5) were named as follows:

Reinforcing loop (R1): "design productivity improvement".
BIM adoption $\rightarrow^{-}$ Rework $\rightarrow^{-}$ Design productivity $\rightarrow^{+}$ Workload completion $\rightarrow^{+}$ Company income $\rightarrow^{+}$ Company budget $\rightarrow^{+}$ BIM adoption.

Reinforcing loop (R^2): "BIM network compatibility".
BIM adoption $\rightarrow^{+}$ BIM adoption of sub-contractors $\rightarrow^{+}$ Network external compatibility $\rightarrow^{+}$ Workload completion $\rightarrow^{+}$ Company income $\rightarrow^{+}$ Company budget $\rightarrow^{+}$ BIM adoption.

Balancing loop (B1): "BIM awareness".
BIM adoption $\rightarrow^{-}$ awareness $\rightarrow^{+}$ BIM adoption.

Balancing loop (B2): "customer satisfaction".
BIM adoption $\rightarrow^{-}$ rework $\rightarrow^{-}$ design quality $\rightarrow^{+}$ customer satisfaction $\rightarrow^{+}$ workload in progress $\rightarrow^{-}$ project participation $\rightarrow^{+}$ awareness $\rightarrow^{+}$ BIM adoption.

Balancing loop (B3): "project participation".
Project participation $\rightarrow^{+}$ workload in progress $\rightarrow^{-}$ project participation.

Balancing loop (B4): "design production".
BIM adoption $\rightarrow^{+}$ rework $\rightarrow^{-}$ design productivity $\rightarrow^{+}$ workload completion $\rightarrow^{+}$ customer satisfaction $\rightarrow^{+}$ workload in progress $\rightarrow^{-}$ project participation $\rightarrow^{-}$ awareness $\rightarrow^{+}$ BIM adoption.

Balancing loop (B5): "design network improvement".
BIM adoption $\rightarrow^{+}$ BIM adoption of sub-contractors $\rightarrow^{+}$ network external compatibility $\rightarrow^{+}$ workload completion $\rightarrow^{+}$customer satisfaction $\rightarrow^{+}$ workload in progress $\rightarrow^{+}$ project participation $\rightarrow^{-}$ awareness $\rightarrow^{+}$ BIM adoption.

The stock-flow diagram

Once the causal loop diagram was completed, all the key variables were transformed into a stock-flow diagram to facilitate the quantitative running of the model using Vensim® (PLE) software version 6.1c (released in June 2013) by Ventana Systems Inc. (Figure 4).

Governing equations

Once the causal relations in terms of the stock-flow diagram were developed, the variables were linked as "governing equations" using a fundamental linear mathematical equation expressed as $Y = aX + b$. Based on historical data from the selected company, all the governing equations were formulated and pasted into the model (using Vensim's format). The ten months' historical data were collected from the company case study using several tools including interviews, a questionnaire and recorded documents. Customer index and other indices were measured using a rating scale (0-100 per cent) questionnaire. The respondents were asked to give values on the scale based on their views on a monthly basis. For some data (e.g. global change and awareness) the respondents were asked to draw "trend lines" (increase or decrease) for the variables over the study period on graph paper with scales based on their opinion and perceptions. The trend lines were converted to measurable values.

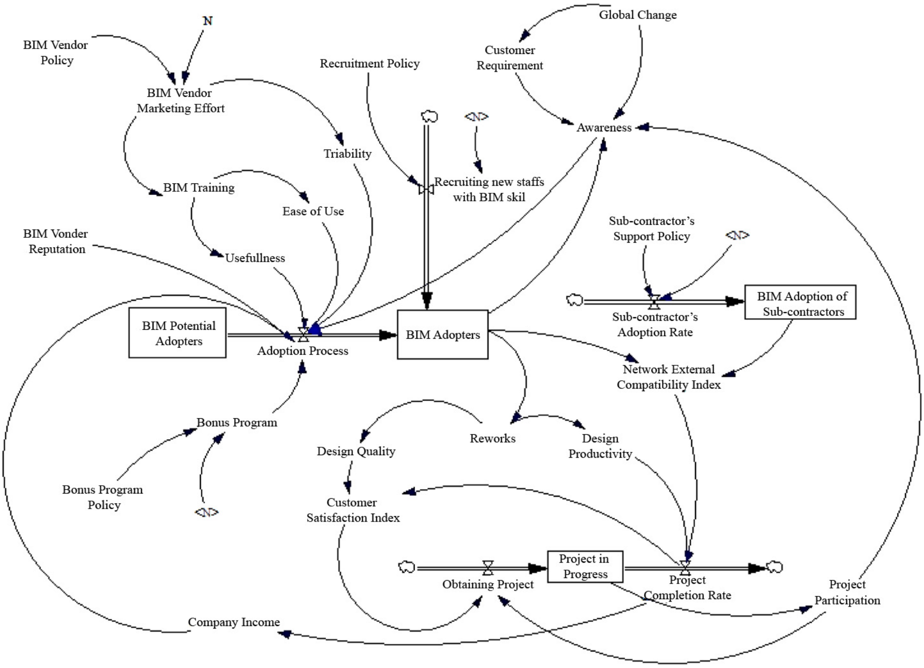


Figure 4.
Stock-flow diagram of BIM adoption in Thai architectural and engineering design firms

An example of the governing equations used to illustrate the relationship between "Project Completion Rate" (an independent variable) and "Company income" (a dependent variable) is shown in Table I:

$$\text{Therefore, Company Income} = 0.052 \times \text{Project Completion Rate} - 0.844 \tag{1}$$

The other governing equations (2) to (26) were formulated and presented in the Appendix.

Model validation

Before quantitative analysis and simulation, it was necessary to ensure that the model dynamically reflected the relationship among the variables. According to Barlas (1994), the model is valid if the error rate is less than 5 per cent. Corroborating this, Suryani *et al.* (2010) added that it must be supported by objective truth. By implication, certain historical data is required to build a model considered fit and reliable. Therefore, the following tests (Sterman, 2000) were conducted to establish accuracy:

Month	1	2	3	4	5	6	7	8	9	10
Project completion rate (million baht/month)	308	395	509	516	526	592	569	532	655	642
Company income (million baht)	15	20	25	26	27	30	28	27	32	34

Table I.
An example of historical data for formulating the governing equations

- *Boundary-adequacy test*: This verifies whether the detailed variables in the model structure are appropriate for the research purpose. All the variables were examined for structural relationships and embodied in the stock-flow diagram. After examining all the variables in the diagrams, each was declared fundamental for the research purpose.
- *Structure verification test*: This ensures that the model structure does not contradict knowledge about the structure of the real system and has the most relevant structures of the real system being modelled. The variables included in the causal loop diagram (Figure 3) were based on several studies and on interviews with experts in this domain. Therefore, the structure of the two diagrams (Figures 3 and 4) was logical and represented a real-life system.
- *Dimension consistency test*: This ensures the consistency of the variable dimensions in every equation balanced on each side of the equations. The governing equations were formulated according to the relationships between the dependent and independent variables which did not demonstrate consistency in terms of dimensions. Therefore, dimension consistency was not considered.
- *Parameter verification test*: This checks the numerical values of the parameters which should have real system equivalents. Figures 5(a) to (f) show some of the selected parameters, comparisons of their simulated values and historical values from data collection.

To assess the model's ability to reproduce the behaviours of a real-life system, the six graphs [Figures 5(a) to (f)] show that the simulated values (curve 2) appropriately fit the historical values (curve 1). The simulated and historical values were relatively similar. The SD model was thus successful in reproducing real data.

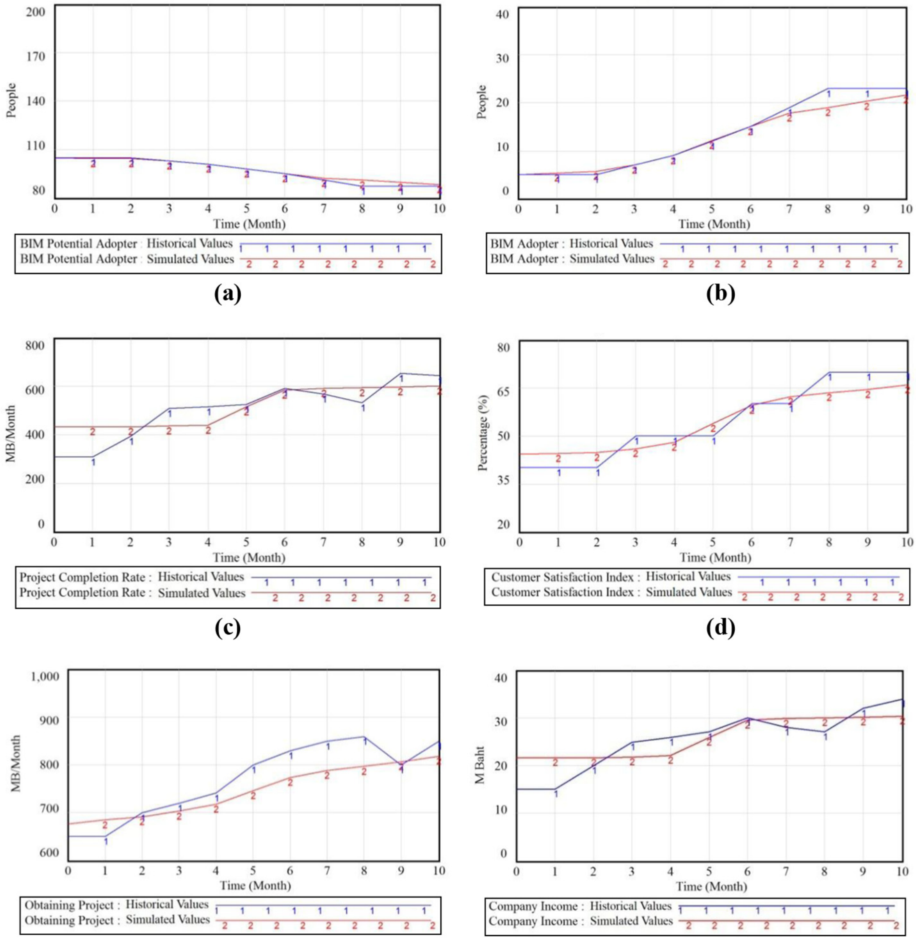
Extreme conditions test. This examines the behaviour of the model by assigning extreme values into the model variables. Does every equation in the model make sense even if subjected to extreme (but possible) values of the variables? To clarify the purpose of the test, the variable "BIM vendor policy" was taken as an example. The impact of "BIM vendor policy" on the "BIM adopter" over time was examined by changing the values from 30 per cent in the second month to 50 per cent in the third month and 80 per cent in the fourth to sixth months (business as usual) to be 100 per cent in all ten months (extreme condition). The findings showed that in the case of a higher support policy from the BIM vendor, "BIM vendor marketing effort" and "BIM training" led to an increase in "BIM adopters" (Figure 6). Figure 6 shows that the simulated output value with extreme value (100 per cent of BIM vendor policy to support marketing effort and training) was reasonable for the output value of the BIM adopter (52 people in the tenth month). Thus, this model made sense even when subjected to extreme values.

Figure 4. Stock-flow diagram of BIM adoption in Thai architectural and engineering design firms

Simulation of the results and discussion

The concept of the balanced scorecard proposed by Kaplan and Norton (1996) stated that a successful organisation should be measured by four perspectives/indicators:

1. financial;
2. customer;
3. internal business processes; and
4. learning and growth.



(a) **(b)**

(c) **(d)**

(e) **(f)**

Figure 5. Examples of the parameter verification test

Notes: (a) BIM potential adopter; (b) BIM adopter; (c) project completion rate; (d) customer satisfaction index; (e) obtaining project; (f) company income

A balanced scorecard is a management tool that provides senior executives with a comprehensive set of measures to assess how the organisation is progressing towards meeting its strategic goals. By using the concept, the authors decided to measure the success of the company using the four indicators:

(1) company income (financial perspective);
(2) the customer satisfaction index (customer perspective);
(3) reworks (internal business process perspective); and
(4) BIM adoption (learning and growth perspective).

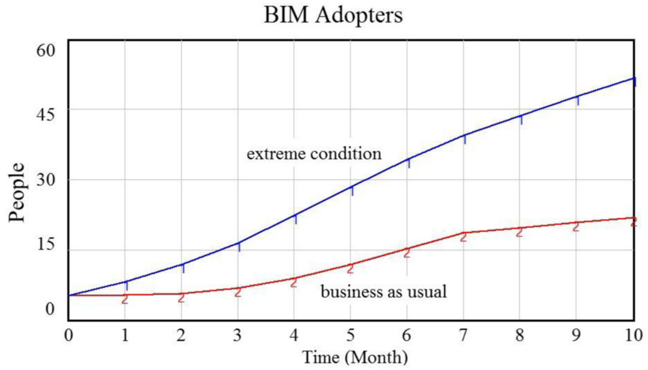


Figure 6. An example of the extreme condition test

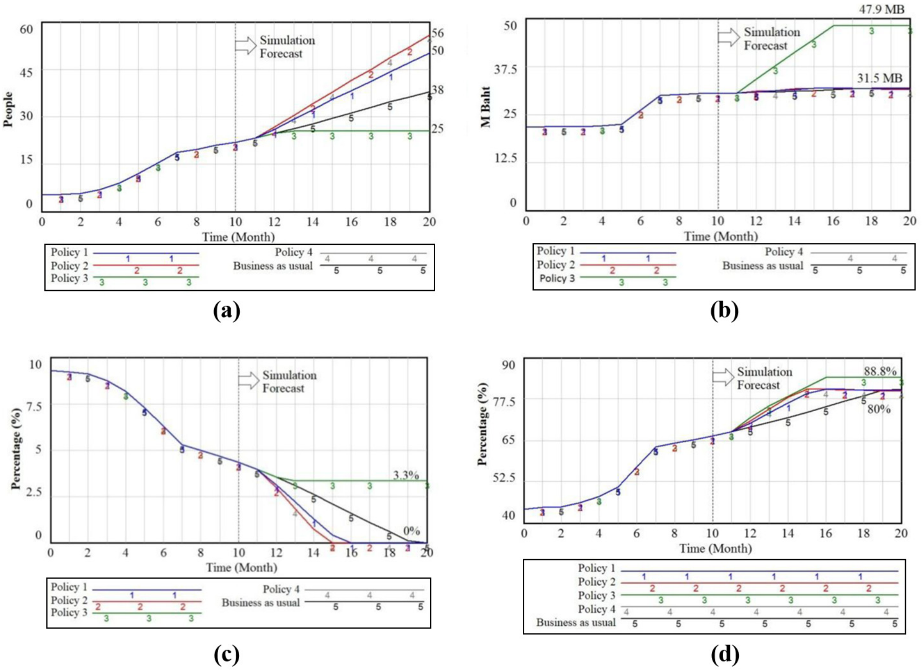
Notes: Curve 1: BIM vendor policy = 100 per cent in all months (extreme condition); Curve 2: BIM vendor policy = 300 per cent in the second month, 50 per cent in the third month and 80 per cent in the forth to sixth month (business as usual)

The validation tests concluded that the model was robust and could be used for simulation and quantitative analysis. The model was simulated over a total period of 20 months to forecast the dynamic behaviour of the company used as the case study. Four policies were formulated from interviews and discussions with the management team of the company including:

- *Business as usual*: "do nothing", conducting business without any policy.
- *Policy 1*: "BIM training", the company organised BIM training courses for existing staff members (50 per cent joined the training between the 11th and 20th month).
- *Policy 2*: "Recruiting new staff members with BIM skills" (two people were recruited on a monthly basis to join the company between the 11th and 20th months).
- *Policy 3*: "Employing design sub-contractors (out-sourcing)", through the engagement of a design sub-contractor (BIM operation) between the 11th to 15th month, on a monthly basis.
- *Policy 4*: "Bonus programme", the company set up a bonus programme for new BIM adopters throughout the 11th and 20th months (assuming two new BIM adopters/month complete the programme). The simulation results are shown in Figure 7.

The policies were compared to establish the simulated outputs for each from the 11th month to the 20th month. With regards to BIM adopters (learning and growth), policies 2 and 4 showed the highest value (56 BIM adopters) by the 20th month [Figure 7(a)].

From the perspective of company income (financial), Policy 3 exhibited the most effective and highest value (47.9m baht) [Figure 7(b)]. From the perspective of reworks (internal business process), policies 1, 2 and 4 and business as usual were effective in reducing rework of the company to zero; however, policies 2 and 4 were the most



Notes: (a) BIM adopters; (b) company income; (c) reworks; (d) customer satisfaction index

Figure 7.
Results of the policy analysis simulation

effective in terms of quick reduction of rework to zero [Figure 7(c)]. Lastly, regarding customer satisfaction, Policy 3 was the most effective (88.8 per cent). Policies 1, 2 and 4 and doing business as usual achieved 80 per cent customer satisfaction by the end of the 20th month, but the most effective were policies 2 and 4 which achieved 80 per cent customer satisfaction by the 15th month [Figure 7(d)]. The values at the end of the 20th month are shown in Table II.

Conclusions

This study developed a system dynamics model to enhance the adoption of BIM in Thai architectural and engineering design firms. Four Thai architectural and engineering design companies were selected as case studies to examine the factors relevant to BIM adoption. The outcome model showed causal relationships among the key variables recommended by the researches (Rowlinson, 2017; Ahuja *et al.*, 2016; Rogers *et al.*, 2015; Ding *et al.*, 2015). Subsequently, one of the four companies was chosen for the collection of quantitative data during a ten-month study period. The collected data (historical data) were used to formulate the governing equations in the SD model. To improve company performance based on the use of the balanced scorecard in building a policy-focused organisation, four policies (i.e. BIM training, recruiting new staff members with BIM skills, employing design sub-contractors and a bonus programme) were formulated through interviews and discussions with the management team of the company, which were compared with operating business as usual. The results revealed that recruiting new staff members with BIM skills and a bonus programme were better choices

Table II.
Results of the simulation within the twentieth month period

Policy comparisons	Values of the simulation within the twentieth month period BIM adopters (people)	Company income (million baht)	Customer satisfaction (%)	Reworks (%)
Business as usual	38	31.8	80.3	0
Policy 1 *"BIM training"*	50	31.5	80.0	0
Policy 2 *"Recruiting new staff members with BIM skills"*	56	31.3	79.9	0
Policy 3 *"Employing design sub-contractor"*	25	47.9	88.8	3.3
Policy 4 *"Bonus programme"*	56	31.3	80.0	0

in terms of increasing the number of BIM adopters within the company. Employing design sub-contractors was the best from a financial perspective (47.9m baht). However, the reworks in company operation were high (3.3 per cent). Overall, BIM training was regarded as the most appropriate policy. This policy is supported by the study of Rogers *et al.* (2015) who found that the lack of well-trained personnel is the most significant barrier to BIM adoption. However, the cost of implementing policies should be considered and compared in practice by company management teams.

The study compared the four policies to provide more in-depth information than Love *et al.* (1999), Love *et al.* (2000) and Ogunlana *et al.* (1998) with quantitative results. However, reworks remain an essential indicator of organisational performance. The results demonstrated the potential applicability and utility of the SD model to improve BIM adoption by architectural and engineering design firms in Thailand. Using these policies, management teams will be able to choose the best options based on company targets to improve operations. Finally, applications of SD can be used as guidelines for other organisations and countries encountering BIM adoption to improve operations.

The limitations of the study included the simulations, which did not cover the cost of implementing the policies and resignations by staff members. These aspects were not considered in the company case study because of lack of information. Recommended areas for future research include using the methodology to study other innovations such as LEED (Leadership in Energy and Environmental Design), 3D printing and new construction materials in the architectural and engineering design industry. Other industries and organisations can also use the model as a guideline to study and forecast the adoption of new technologies in their field, such as using robotic machines for manufacturing and employing smart phones or other devices in construction site inspection and supervision.

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Appendix

No.	Governing equations
1	Company income = 0.052 × Project completion rate − 0.844
2	BIM vendor marketing effort = BIM vendor policy (*N*)
3	BIM training = 16.343 + 1.052 × BIM vendor marketing effort
4	Usefulness = BIM training
5	Ease of use = BIM training
6	Trialability = BIM vendor marketing effort
7	Adoption process = 0.0125 × Usefulness + 0.0125 × Ease of use + 0.001 × Triability − 0.035 × Awareness − 0.216 × Company income + 0.0805 × BIM vendor reputation + Bonus programme
8	Recruiting new staffs with BIM skill = Recruitment policy (*N*)
9	Awareness = 273.186 − 0.13 × Customer requirement – 0 × Global change − 1.662 × Project participation − 8.042 × BIM adopters
10	Global change = STEP (100, 1)
11	Sub-contractor's adoption rate = "Sub-contractor's support policy"(*N*)
12	Network external compatibility index = 3.74 − 0.325 × BIM adopters + 37.126 × BIM adoption of sub-contractors
13	Reworks = 10.745 − 0.294 × BIM adopters
14	Design quality = 80.909 − 3.471 × Reworks
15	Design productivity = 80.909 − 3.471 × Reworks
16	Customer satisfaction index = −16.279 + 0.86 × Design quality + 0.043 × Project completion rate
17	Obtaining project = 694.039 + 3.598 × Customer satisfaction index − 1.805 × Project participation
18	Project completion rate = 304.383 + 2.558 × Design productivity + 1.788 × Network external compatibility index
19	Project participation = 97.107 − 0.015 × Project in progress
20	BIM potential adopters = −Adoption rate (Initial value = 105 people)
21	BIM adopters = Adoption rate + Recruiting new staff with BIM skills (Initial value = 5 people)
22	BIM adoption of sub-contractors = "Sub-contractor's adoption rate" (Initial value = 0 people)
23	Project in progress = Obtaining project − Project completion rate (Initial Value = 1,050m baht)
24	BIM vendor policy = [(1,0) – (10,80)], (1,0), (2,30), (3,50) ,(4,80), (5,80), (6,80), (7,0), (8,0), (9,0), (10,0)
25	BIM vendor reputation = 100
26	Recruitment policy = [(1,0) – (10,2)], (1,0), (2,0), (3,0), (4,0), (5,0), (6,0), (7,0), (8,0), (9,0), (10,0)
27	Sub-contractor's support policy = [(1,0) – (10,2)], (1,0), (2,0), (3,0), (4,0), (5,1), (6,10), (7,0), (8,0), (9,0), (10,0)

Table A1.
Governing equations

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