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Examining the effect of interoperability factors on building information modelling (BIM) adoption in Malaysia

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Received 28 December 2021
Revised 20 April 2022
31 August 2022
Accepted 14 September 2022

Abstract

Purpose – Building information modelling (BIM) has transformed the traditional practices of the Architecture, Engineering and Construction (AEC) industry. BIM creates a collaborative digital representation of built environment data. Competitive advantage can be achieved with collaborative project delivery and rich information modelling. Despite the abundant benefits, BIM's adoption in the AEC is susceptible to confrontation. A substantial impediment to BIM adoption often cited is data interoperability. Other facets of interoperability got limited attention. Other academic areas, including information systems, discuss the interoperability construct ahead of data interoperability. These interoperability factors have yet to be surveyed in the AEC industry. This study aims to investigate the effect of interoperability factors on BIM adoption and develop a comprehensive BIM adoption model.

Design/methodology/approach – The theoretical foundations of the proposed model are based on the European interoperability framework (EIF) and technology, organization, environment framework (TOE). Quantitative data collection from construction firms is gathered. The model has been thoroughly examined and validated using partial least squares structural equation modelling in SmartPLS software.

The authors want to show their appreciation and thank the respondents who provided feedback on the questionnaire. Further, the authors thank the SIMAD University, Mogadishu, Somalia, for funding this research.

Data availability statement: Some or all data, models or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Construction Innovation

1471-4175
DOI 10.1108/CI-12-2021-0245

Findings – The study’s findings indicate that relative advantage, top management support, government support, organizational readiness and regulation support are determinants of BIM adoption. Financial constraints, complexity, lack of technical interoperability, semantic interoperability, organizational interoperability and uncertainty are barriers to BIM adoption. However, compatibility, competitive pressure and legal interoperability do not affect BIM adoption.

Practical implications – Finally, this study provides recommendations containing the essential technological, organizational, environmental and interoperability factors that AEC stakeholders can address to enhance BIM adoption.

Originality/value – To the best of the authors’ knowledge, this paper is one of the first studies to combine TOE and EIF in a single research model. This research provides empirical evidence for using the proposed model as a guide to promoting BIM adoption. As a result, the highlighted determinants can assist organizations in developing and executing successful policies that support BIM adoption in the AEC industry.

Keywords BIM interoperability, Interoperability factors, BIM adoption model, BIM determinants

Paper type Technical paper

1. Introduction

The construction sector’s key challenges are automation, digitization, mimetic pressure and greater capital value (Ozener *et al.*, 2020; Faisal Shehzad *et al.*, 2020; Mohammad *et al.*, 2019). A competitive advantage is achieved through collective project execution and information processing (Fan *et al.*, 2019; Aka *et al.*, 2020; Brito *et al.*, 2021). Building information modelling (BIM) offers identification, collision detection, project control, environmental analysis, risk assessment, site control, 3D modelling, design preparation and simulation (Bosch-Sijtsema *et al.*, 2019). To make the entire building process easier, BIM creates a collaborative digital representation of built environment data. It helps model the designing, scheduling, estimation, construction and delivery of the project (Ismail *et al.*, 2019; Moreno *et al.*, 2019; Lu *et al.*, 2020). Current BIM adoption studies addressed the adoption barriers and drivers in the Architecture, Engineering and Construction (AEC) industry (Ozener *et al.*, 2020; Al-Hammadi and Tian, 2020; Chen *et al.*, 2019; Georgiadou, 2019; Gong *et al.*, 2019; Ma *et al.*, 2019; Mohammad *et al.*, 2019; Park *et al.*, 2019). Ahmed and Kassem (2018) developed a taxonomy of BIM drivers in the UK. Cao *et al.* (2017) discuss motivations at the individual level to adopt BIM in China’s architects and identify motives in adopting BIM. Howard *et al.* (2017) identified individual perceptions about BIM prevailing among UK architects. A few studies discuss BIM readiness and acceptance in design organizations and identify BIM adoption inhibitors that hinder BIM adoption on a broader scale (Ahuja *et al.*, 2016; Juan *et al.*, 2017). Similarly, most of the studies discussed BIM adoption at the project level (Cao *et al.*, 2016; Merschbrock and Nordahl-Rolfsen, 2016) and individual level (Song *et al.*, 2017; Hong and Yu, 2018; Van Tam *et al.*, 2021). However, organizational-level BIM adoption studies are limited.

Existing studies show that technology factors influence innovation adoption, but many organizational factors influence technology adoption (Chen *et al.*, 2019; Seyis, 2019; Shehzad *et al.*, 2019). Furthermore, BIM adoption is influenced by organizational variables such as inter-organizational processes, policies and practices. For example, a study tested the corporate adoption of digital technologies and found that organizational culture directly influences its intention to use technologies (Yoon and George, 2013; Dao and Chen, 2021; Yang *et al.*, 2021). Although these studies offer valuable insight into organizational issues, research that explores specific organizational challenges, such as organizational interoperability, also remains to be accomplished. Existing research on innovation in the building industry demonstrates that the use of technology is not only driven by the need for productivity to solve internal process problems efficiently and effectively (Toinpre *et al.*, 2018; Manzoor *et al.*, 2021; Hire *et al.*, 2022). As the construction industry relies on many external bodies, such as government and industry associations, it can affect BIM adoption (Babič and Rebolj, 2016; Mohammad *et al.*, 2019; Ramanayaka and Venkatachalam, 2015). Therefore, it is vital to test the impact of environmental factors on BIM implementation.

Interoperability is defined as "the capabilities of information and communication technology (ICT) systems and the operational processes they facilitate to exchange data and share information and knowledge" (EIF, 2004). According to research by Venugopal *et al.* (2015), the USA capital facilities business spends $15m a year on efficiency losses due to interoperability challenges. The issues in platform interoperability are the key impediments to the market adoption of BIM (Grilo and Jardim-Goncalves, 2010; Muller *et al.*, 2015). Another research highlights interoperability because many structural engineers use computational and structural modelling software that uses formats other than the BIM and industry foundation class (IFC) standards (Liu *et al.*, 2016; Arayici *et al.*, 2018; Shehzad *et al.*, 2021a, 2021b, 2021c).

The main barriers to adopting BIM by the market are the difficulties in interoperability among platforms (Grilo and Jardim-Goncalves, 2010; Muller *et al.*, 2015). The study of Liu *et al.* (2016) points to the interoperability problem because many structural engineers often adopt computational and structural modelling software with different formats from BIM and IFC standards. In a recent study, Pishdad-Bozorgi *et al.* (2018) suggest that facility management-enabled BIM is achieved with a well-executed interoperability plan for exchanging data between BIM tools and facility management systems. Interoperability enables model sharing and linking data between different operators, and BIM applications ensure data consistency (Tommasi and Achille, 2017). Addressing the interoperability challenges requires a shared understanding among construction stakeholders and flexibility needs in environments (Arayici *et al.*, 2018). Interoperability bounds are inside a particular BIM environment and outside an organization using a BIM application, and it is essential to consider other factors affecting interoperability (Tommasi and Achille, 2017).

This study investigates the effect of interoperability factors on BIM adoption and develops a comprehensive BIM adoption model. The study's contribution is to combine and categorize the factors into four dimensions and explain their relationship. The study is organized in the following way. Section 2 discusses the related literature. Research methodology and model development are presented in Sections 3 and 4. The data analysis results are shown in Section 5. Finally, the conclusion is presented in Section 6.

2. Literature review

BIM offers construction planning, 3D modelling, visualization, cost estimation, forensic analysis, facilities management, project management, collision detection and fabrication (Grilo and Jardim-Goncalves, 2010; Shehzad *et al.*, 2021a, 2021b, 2021c). The central core of BIM is providing information integration and collaboration between the construction project stakeholders (Juan *et al.*, 2017; Shehzad *et al.*, 2021a, 2021b, 2021c). The successful BIM implementation enhances stakeholders' capabilities to manage and plan construction activities. Interoperability relates to the capacity of ICT technologies and the business processes they facilitate to communicate data, information and knowledge. The interoperability of BIM influences joint project delivery systems (Olawumi *et al.*, 2018; Pishdad-Bozorgi *et al.*, 2018; Muhammad *et al.*, 2020). Because of the information processing aspect of such systems, a better understanding of interoperability is required for more successful and efficient project delivery. The issues in platform interoperability are the key impediments to the market adoption of BIM (Grilo and Jardim-Goncalves, 2010; Muller *et al.*, 2015).

The interoperability of data is frequently highlighted as a major obstacle to BIM adoption (Xu *et al.*, 2014). Pauwels *et al.* (2017) suggest semantic Web technology for improving data interoperability. The study by Liu *et al.* (2016) highlights that many engineers use computational and structural modelling software which supports different data standards, posing an interoperability difficulty. The majority of existing BIM research focuses on technological interoperability, including data integration and validation using IFC (Lee *et al.*, 2015; Matějka *et al.*, 2016). Another research defines ontologies as cross-discipline data mapping, as well as data object integration across domains (Lee *et al.*, 2015; Zhang *et al.*, 2017). Only a few studies have been undertaken to identify technological interoperability concerns for BIM adoption (Muller *et al.*, 2017; Poirier *et al.*, 2014; Xu *et al.*, 2014).

Barriers to BIM adoption have been explored in existing studies (Herr and Fischer, 2018). The interoperability of BIM is the influencing factor effect on collaborative project delivery systems (CPDSs) (Olawumi *et al.*, 2018; Pishdad-Bozorgi *et al.*, 2018). The information processing nature of CPDS requires a broader conceptualization of interoperability to make more effective and efficient project delivery. Therefore, it is necessary to understand interoperability and the drivers of interoperability, and the factors that contribute to low BIM adoption. However, there is limited literature on factors and dimensions of interoperability affecting BIM adoption. Moreover, there is a need to identify other interoperability dimensions, such as legal interoperability and semantic interoperability. There is also a lack of a comprehensive framework for addressing interoperability issues in the current studies. Therefore, it is vital to assess the impact of interoperability factors on BIM adoption.

However, the focus of BIM research is mostly on technical interoperability, such as data validation with IFC (Lee *et al.*, 2015) and data integration with IFC to increase data interoperability (Matějka *et al.*, 2016). Other studies include defining ontologies for mapping cross-discipline data (Lee *et al.*, 2015), use of the semantic Web for enhancing data interoperability (Pauwels *et al.*, 2017) and integration of data objects in different fields (Karam *et al.*, 2018). Few studies are addressing organizational interoperability (Zhang *et al.*, 2017). There are limited studies that stress finding interoperability issues in other dimensions along with technical dimensions (Poirier *et al.*, 2014; Xu *et al.*, 2014; Muller *et al.*, 2017). Based on the current literature review, it is evident that existing studies discuss only technical interoperability in the BIM domain, whereas interoperability in the other three dimensions is missing in current standards. Similarly, legal interoperability, semantic interoperability and organizational interoperability are yet to be explored. Therefore, it is essential to realize interoperability factors influencing BIM adoption (Karam *et al.*, 2018; Wong *et al.*, 2018; Zhu *et al.*, 2018; Arshad, 2019).

2.1 State of building information modelling implementation in the Architecture, Engineering and Construction industry in Malaysia

BIM in Malaysia was introduced in 2007 (Latiffi *et al.*, 2016). According to a current report by the Construction Industry Development Board (CIDB), a significant awareness level of BIM is recorded in the construction industry, and 84% of firms have the intention to adopt BIM (CIDB Malaysia, 2017). However, the current adoption rate of BIM is very low, and only 17% of design firms have adopted BIM. Other AEC firms, such as engineering firms and construction firms, have yet to adopt BIM (Hanafi *et al.*, 2016). The Malaysian construction industry is currently falling at level one BIM implementations, and the rest of the world is striving for level four and beyond. It indicates that BIM adoption in the construction industry is low. Even the readiness level of BIM was recorded as very low, and 41% of the organizations are unable to implement BIM due to a lack of BIM policies (CIDB, 2017).

2.2 Determinants of building information modelling implementation in the Architecture, Engineering and Construction industry

Factors affecting BIM adoption are categorized into three dimensions: organizational, technology and environment. Organizational factors are related to inter-organizational processes, practices and policies that affect BIM adoption. Many factors are pointed out in studies affecting BIM adoption, as summarized in Tables 1–3. As depicted in the table, the most affecting factor is top management support (Son *et al.*, 2014, 2015; Ahuja *et al.*, 2016; Song *et al.*, 2017; Okakpu *et al.*, 2018). Technological factors cover BIM tool-related factors affecting the actual use and implementation of technology. The most dominating factors in this category are compatibility and complexity (Gao *et al.*, 2013; Xu *et al.*, 2014; Seed, 2015; Ahuja *et al.*, 2016; Kim and Yu, 2016). Environmental factors are the factors outside of the organization that influences in the form of isomorphism. Isomorphism includes mimetic pressure, normative pressure and coercive pressure.

2.3 Challenges to building information modelling implementation in the Architecture, Engineering and Construction industry

Several factors influence BIM adoption, such as lack of industry readiness (Yusuf *et al.*, 2017), lack of awareness (Hamid *et al.*, 2018), lack of government initiatives (Mustaffa *et al.*, 2017), lack of BIM professionals (Enegbuma *et al.*, 2016) and resistance to change (Mehran 2016). Other factors include lack of infrastructure (Btoush and Haron, 2017), social issues such as normative pressure (Bosch-Sijtsema *et al.*, 2017) and technical issues such as interoperability and cost of implementation (Ghaffarianhoseini *et al.*, 2017). In addition to trialability and BIM quality (Ngowtanasawan, 2017), legal issues (Walasek and Barszcz, 2017), internal and external factors (Ahmed *et al.*, 2017), willingness to adopt BIM (Juan *et al.*, 2017) and cultural differences (Herr and Fischer, 2018) also effect on BIM adoption.

2.4 Theoretical foundations of the study

Technology adoption is the acceptance and use of new technology. Studies on adoption focus on understanding, predicting and finding the influencing factors at organizational and individual levels. Such research guided the development of frameworks and models to assess the use and influence of technology acceptance factors (Date *et al.*, 2014). Theory of planned behaviour (TPB): the theory of planned behaviour declares that a person's intention to do any act is based on individual attitude towards that action and perceived behavioural control and subjective norms. The TPB provides a psychological model to study behaviour. It explains that people have more control over behaviours that need less effort and resources than behaviours that require more effort (Salahshour *et al.*, 2017). Perceived behavioural control plays its role as a proxy to demonstrate the difficulty or easiness of doing a particular behaviour (Ajzen, 1991). Technology acceptance model (TAM): TAM is developed by Davis (1989) and is the most widely used acceptance model. It explains the role of attitude, intention and behaviour in accepting or rejecting technologies. According to TAM, external variables influence perceived ease of use and perceived usefulness and attitude. Attitude leads to behavioural intention. Behavioural Intention influences actual use. The unified theory of acceptance and use of technology (UTAUT): UTAUT is the combination of eight theories, including TAM, theory of reasoned action (TRA), combined TAM and diffusion of innovations (DOI), to predict behavioural intentions to use technology. It is also a widely used theory as it contains elements from other theories also. However, it has some limitations and is revised by Venkatesh *et al.* (2003). This theory consists of seven components: facilitating conditions, social influence, performance expectancy, effort expectancy, behavioural intention and use behaviour. DOI: the DOI

Table 1. Organizational factors affect BIM adoption

References	Business agility	Facilitation conditions	Fidelity	Cost constraints	Clarity of project	Uncertainty	Cultural norms	Economic motivations	Financial sustainability	Lack of experts	Lack of IT support	Lack of procurement methods	Management policies
Takim *et al.* (2013)	*		*	*	*	*			*				
Son *et al.* (2015)		*				*							
Xu *et al.* (2014)				*						*			
Gao *et al.* (2013)				*		*							
Yoon and George (2013)							*						
Cao *et al.* (2016)								*					
Juan *et al.* (2017)									*				
Ramanayaka and Venkatachalam (2015)									*			*	
Merschbrock and Munkvold (2015)											*		*
Kim *et al.* (2016)													
Lee *et al.* (2015)													
Enegbuma *et al.* (2014)													
Okakpu *et al.* (2018)													
Ahuja *et al.* (2016)													
Son *et al.* (2014)													
Song *et al.* (2017)													
Kim *et al.* (2016)						*							
Hosseini *et al.* (2016)						*							

Note: *Factor found in existing study

(*continued*)

Table 1.

References	Organizational readiness	No observability	Organizational competency	Organizational variety	Perceived risk	Process perceptions	Reactive motives	Structure optimization	Top management support	Traditional practices	Uncertain investment
Takim *et al.* (2013)	*										
Son *et al.* (2015)	*										
Xu *et al.* (2014)	*										
Gao *et al.* (2013)	*										
Yoon and George (2013)											
Cao *et al.* (2016)							*				
Juan *et al.* (2017)	*										
Ramanayaka and Venkatachalam (2015)											
Merschbrock and Munkvold (2015)	*										
Kim *et al.* (2016)		*									
Lee *et al.* (2015)				*							
Enegbuma *et al.* (2014)						*					
Okakpu *et al.* (2018)								*	*		
Ahuja *et al.* (2016)									*		
Son *et al.* (2014)									*		
Song *et al.* (2017)									*		
Kim *et al.* (2016)										*	
Hosseini *et al.* (2016)										*	*

Table 2.
Technological factors affect BIM adoption

References	Interoperability	Trialability	Accessibility	Compatibility	Competitive advantage	Complexity	Functionality
Xu *et al.* (2014)	*			*	*	*	
Ahuja *et al.* (2016)		*					
Gao *et al.* (2013)		*		*			
Seed (2015)		*		*	*		
Merschbrock and Munkvold (2015)	*		*	*			*
Son *et al.* (2015)				*			
Son *et al.* (2014)		*		*		*	
Kim *et al.* (2016)				*			
Takim *et al.* (2013)		*			*		
Ahuja *et al.* (2018a)	*					*	
Song *et al.* (2017)	*						
Juan *et al.* (2017)	*	*					
Enegbuma *et al.* (2014)							
Lee *et al.* (2015)							
Okakpu *et al.* (2018)							

Note: *Factor found in existing study

(*continued*)

Table 2.

References	Information quality	Result demonstrability	Relative advantage	Technical support	Technology perceptions	Technology quality	Visualization
Xu *et al.* (2014)			*				*
Ahuja *et al.* (2016)							
Gao *et al.* (2013)							
Seed (2015)							
Merschbrock and Munkvold (2015)			*				
Son *et al.* (2015)			*				
Son *et al.* (2014)			*				
Kim *et al.* (2016)							
Takim *et al.* (2013)				*			
Ahuja *et al.* (2018a)			*				
Song *et al.* (2017)	*					*	
Juan *et al.* (2017)				*			
Enegbuma *et al.* (2014)			*		*		
Lee *et al.* (2015)			*			*	
Okakpu *et al.* (2018)						*	

Table 3. Environmental factors affect BIM adoption

Reference	Economic demand	Lack of policies	Appropriate contracts	Building codes	Championship	Coercive pressure	Competitor motivation	Cross-party knowledge sharing	Cross Project motivations	External services providers
Takim *et al.* (2013)	*	*			*		*			
Ramanayaka and Venkatachalam (2015)		*					*			
Merschbrock and Nordahl-Rolfsen (2016)			*							
Gao *et al.* (2013)				*	*					
Cao *et al.* (2014)						*				
Babič and Rebolj (2016)						*				
Juan *et al.* (2017)							*			
Merschbrock and Munkvold (2015)								*		
Cao *et al.* (2016)							*		*	
Song *et al.* (2017)										*
Juan *et al.* (2017)										
Hosseini *et al.* (2016)							*			
Babič and Rebolj (2016)										
Yoon and George (2013)										
Bosch-Sijtsema *et al.* (2017)										
Liu *et al.* (2018)										
Okakpu *et al.* (2018)										
Babič and Rebolj (2016)										
Ahuja *et al.* (2018a)										
Gao *et al.* (2013)										
Okakpu *et al.* (2018)										
Son *et al.* (2014)										
Son *et al.* (2015)										

Note: *Factor found in existing study

(*continued*)

Table 3.

Reference	Governmental policies	Lack of protocols	Lack of customer support	lack of BIM standard	Lack of interest	Mimetic pressures	Normative Pressure	Open discussion environment	Regulation support	Stakeholders' interaction	Subjective norms
Takim *et al.* (2013)									*		*
Ramanayaka and Venkatachalam (2015)	*										
Merschbrock and Nordahl-Rolfsen (2016)											
Gao *et al.* (2013)	*										
Cao *et al.* (2014)	*					*	*				
Babič and Rebolj (2016)	*										
Juan *et al.* (2017)											
Merschbrock and Munkvold (2015)									*		
Cao *et al.* (2016)	*										
Song *et al.* (2017)											
Juan *et al.* (2017)	*										
Hosseini *et al.* (2016)					*						
Babič and Rebolj (2016)						*					
Yoon and George (2013)							*				
Bosch-Sijtsema *et al.* (2017)							*				
Liu *et al.* (2018)							*				
Okakpu *et al.* (2018)							*				
Babič and Rebolj (2016)							*				
Ahuja *et al.* (2018a)									*		
Gao *et al.* (2013)									*		*
Okakpu *et al.* (2018)										*	
Son *et al.* (2014)											*
Son *et al.* (2015)											*

theory is proposed by Rogers (1995). DOI is based on the belief that innovation diffusion determinants are innovation attributes. The theory's construct includes observability, complexity, compatibility, trialability and relative advantage. TRA: TRA is developed by Fishbein and Ajzen (1975), is a social science theory, and is applied in many areas. The TRA is used to find relationships between attitude and behaviour concerning human action. It measures how an individual behaves with existing behavioural intention and attitude. The constructs of TRA are the attitude towards the act of behaviour and the subject norm. Attitude and behaviour influence behavioural intentions and behavioural intentions influence actual behaviour. Information system success model (ISSM): The ISSM is developed by DeLone and McLean (1992) and evaluates its failure or success. This model's independent constructs are system quality, information quality and service quality. Information quality measures the semantic dimension of information, and system quality measures technical success. The independent variable affects the Intention to use and user satisfaction. Use and user satisfaction assess the overall system effectiveness. Institutional theory: institutional theory is developed by Scott (2004), and it focuses on the role of the institutional environment in shaping behavioural changes and obtaining social legitimacy. The primary construct of this theory is isomorphism. Three types of isomorphic pressure are coercive, mimetic and normative. Coercive isomorphism is the study of changes due to pressure from an external organization. Mimetic isomorphism focuses on imitating one organization's hierarchical form in the hopes of reaping the same advantages as other organizations. The pressure from regulatory bodies and practitioners interested in licenses and certifications is known as normative isomorphism.

The technology, organization, environment (TOE) framework can better-described the innovation process at the enterprise level. It is developed by Tornatzky and Fleischer (1990). TOE has three dimensions: technology, organization and environment. BIM adoption is a complex phenomenon with varying perspectives and is better explained by the TOE (Ahuja *et al.*, 2016, 2018b; Chen *et al.*, 2019; Mohammad *et al.*, 2019; Shehzad *et al.*, 2021a, 2021b, 2021c). The first motivation to use TOE is because BIM adoption is a very revolutionary process that requires a detailed assessment before implementation. Secondly, BIM is a community-oriented technology that facilitates collaboration among construction industry players by providing coordination and interfaces. Therefore, the issues of interoperability need an assessment before adoption. Thirdly, BIM adoption is an institutional decision and requires organizations to assess available resources and staff capabilities.

The European interoperability framework (EIF) is a widely agreed-upon solution to delivering interoperable IS services. It sets out basic interoperability concepts, models and recommendations in universal principles, models and offers (EIF, 2017). According to the EIF, interoperability is classified into semantic interoperability, organizational interoperability, legal interoperability and technical interoperability. The EIF gives guidance, through a set of recommendations, to public administrations on how to improve governance of their interoperability activities, establish cross-organizational relationships, streamline processes supporting end-to-end digital services and ensure that existing and new legislation do not compromise interoperability efforts. The EIF is the most widely used framework to test technology interoperability in collaborative technologies, such as in the case of BIM (Pishdad-Bozorgi *et al.*, 2018). Therefore, this study applies EIF and TOE to test the effect of interoperability on BIM adoption.

3. Research model and hypotheses

This research study performed systematic literature review (SLR) to identify all factors from existing studies that influence BIM adoption. A pool of factors extracted from SLR is further analyzed to select the research model's factors. For the selection of factors, the method represented in Jeyaraj *et al.* (2006) is suggested (Salahshour *et al.*, 2017; Kim *et al.*, 2018). In the first stage, the factors are categorized into organizational, technology, environment and interoperability dimensions. The current research adopts 14 variables from theories and frameworks to suggest a theoretical BIM adoption model. Based on existing studies in the literature review section, 10 variables have been taken from TOE, and four from EIF, as shown in Figure 2.

3.1 Technological dimension

Relative advantage is "the extent that an invention is regarded as superior to that same concept it replaces" (Rogers, 2003). This study defines the relative advantage as "how BIM provides improved benefits to AEC stakeholders than existing tools" (Chen *et al.*, 2019):

H1. BIM's relative advantage positively influences its adoption.

Complexity is "the extent to that an invention is thought to be hard to grasp and implement" (Rogers, 2003). Even though BIM is believed to be beneficial, firms find it difficult to implement (Xu *et al.*, 2014). When innovation is viewed as difficult to use, people value it less valuable, which contributes to its low adoption (Euisoon and Kim, 2016; Son *et al.*, 2015):

H2. BIM's complexity negatively influences its adoption.

Compatibility is "the extent that an invention is regarded to be congruent with potential users' existing values, past experiences, and needs" (Rogers, 2003). It shows the compliance of old and emerging technologies, as well as their impact on views of system utility (Son *et al.*, 2015). Also, it refers to process integration with the construction sector and compatibility with existing facilities (Díaz *et al.*, 2017) and the user's working style, job functions and performance expectancy:

H3. BIM adoption is influenced by its compatibility with existing applications and practices.

3.2 Organizational dimension

Top management support is perceived as the management's willingness to implement technology and provide necessary resources for technology's proper functioning. Terms of financial decisions must adopt technology and realize benefits to employees and provide technology use guidelines. It also includes psychological support from management (Son *et al.*, 2015):

H4. Top management support positively influences BIM adoption.

Organizational readiness refers to technological infrastructure and skilled professionals having the technical expertise to implement the new technology (Parasuraman and Colby, 2015). Several pieces of research have looked into the impact of organizational readiness on technology adoption (Hosseini *et al.*, 2016; Juan *et al.*, 2017; Merschbrock and Nordahl-Rolfsen, 2016):

H5. Organizational readiness positively influence BIM adoption.

Financial constraints refer to the software cost, the cost of training and the cost of the initial setup. In addition, BIM applications require a high initial set-up cost, application cost, environment set-up cost (Ahuja *et al.*, 2016) and additional BIM services cost (Koo *et al.*, 2017). This perceived cost is negatively associated with BIM adoption:

H6. Financial constraints are negatively related to BIM adoption.

Uncertainty is a feeling of skepticism among technology adopters, as well as apprehension regarding the expectations and delivery of technological innovation to fulfil corporate efficiency needs. It is a barrier to innovation adoption (Rogers, 2003). It includes privacy issues, security, risk of an investment, lack of data ownership and uncertainty in data (Jin *et al.*, 2017; McArthur, 2015). Due to the current ambiguity about return on investment, construction stakeholders are hesitant to invest in BIM (Latiffi and Tai, 2017):

H7. Perceived high uncertainty negatively affects BIM adoption.

3.3 Environment dimension

The pressure from other organizations in the same industry is known as *competitive pressure*. It has an impact on a company's incentives to develop new products and processes. It has been highlighted as a critical component in the literature (Babič and Rebolj, 2016; Desbien, 2017):

H8. Competitive pressure positively influences BIM adoption.

Government support "can have either a beneficial or a detrimental effect on innovation. When governments impose new constraints on the industry, innovation is essentially mandated for those firms" (Baker, 2012). The government directly or indirectly influences technology innovation and is the leading investor in technology in most countries. If a government mandates BIM in construction projects, its adoption rate will ultimately be increased (Dong and Martin, 2017):

H9. Government support positively influences BIM adoption.

Regulatory support included standardization and policies to improve or regulate the use of technologies. It includes the informal and formal restrictions imposed on an organization's activities as a result of government laws or industry standards dictating what the organization can perform (Baker, 2012). According to published research on BIM adoption, regulatory support is the most important element influencing its adoption (Ahuja *et al.*, 2017; Ramanayaka and Venkatachalam, 2015):

H10. Regulatory support positively influences BIM adoption

3.4 Interoperability dimension

Technical interoperability "means the ability of ICT systems, and of the business processes they support to exchange data and to enable the sharing of information and knowledge" (EIF, 2017). Open interfaces, connectivity services, data integration and middleware, data presentation and sharing are just a few of the major features" (EIF, 2004):

H11. Low technical interoperability negatively influences BIM adoption

Organizational interoperability "involves identifying company objectives, modelling workflows, and connecting organizations together which want to share data and had distinct organizational processes and structures" (EIF, 2004). Furthermore, organizational interoperability "attempts to meet the needs of users by keeping services accessible, clearly recognized, available, and user-friendly" (Chen, 2006):

H12. Low organizational interoperability negatively influences BIM adoption.

Semantic Interoperability is:

> Assuring that any other applications which were not originally built for this purpose can understand the precise meaning of transferred information. It allows them to integrate data received with many other data sources and interpret it in a significant way (EIF, 2004).

Previous research indicates that semantic interoperability is a determining aspect of BIM adoption (Howell *et al.*, 2016; Pauwels *et al.*, 2017):

H13. Low semantic interoperability negatively influences BIM adoption.

Legal interoperability is "assuring that companies with varying legal frameworks, policies, and agendas can collaborate" (EIF, 2017). In the building sector, it is standard procedure to submit models and documents to public bodies and authorities for legal approval. Most agencies are unfamiliar with BIM digital modelling and insist on printed models. 3D printing is still in its infancy, and there are still inconsistencies in processes and drawings. Because of the lack of legal interoperability, the contractors are unable to use BIM:

H14. Lack of legal interoperability negatively influences BIM adoption.

4. Research methodology

The research methodology adopted in this study consist of five steps:

1. model development;
2. instrument measurement;
3. instrument validation;
4. data collection; and
5. data analysis, as shown in Figure 1.

Quantitative research is a research strategy that focuses on quantifying the collection and analysis of data. It is formed from a deductive approach where the emphasis is placed on the testing of theory, shaped by empiricist and positivist philosophies. As the objective of the

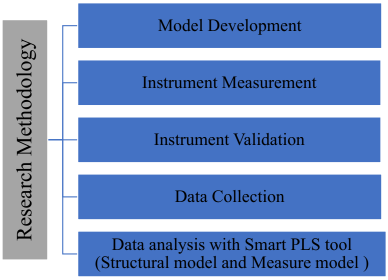

Figure 1.
Research methodology steps

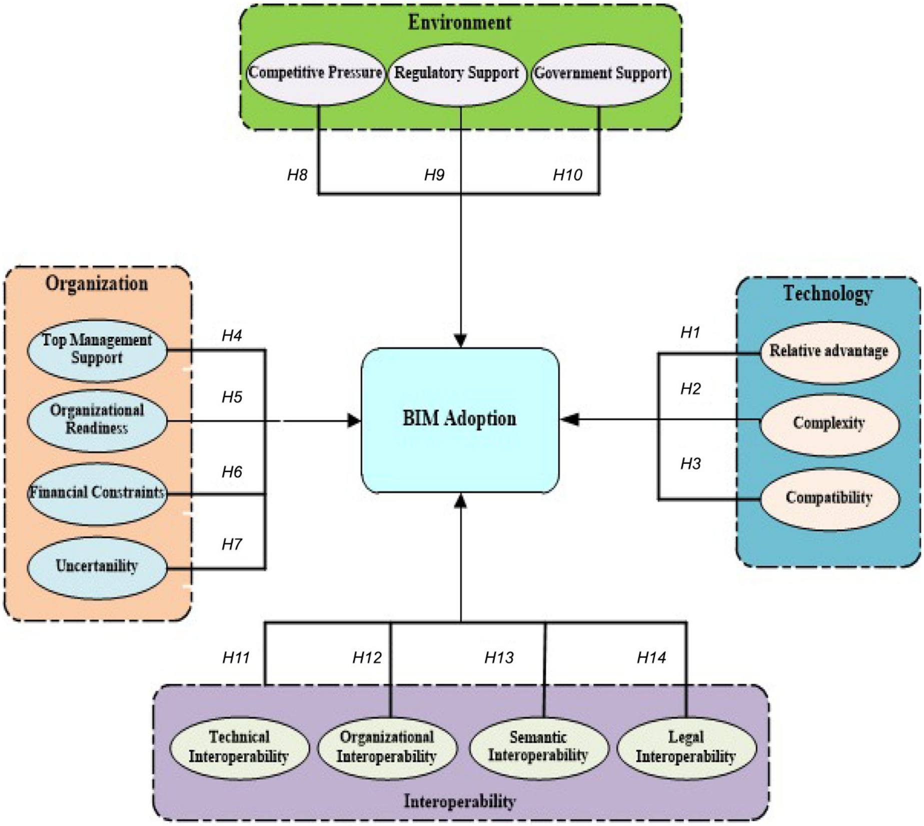

Figure 2.
Proposed BIM adoption model

study is to confirm or test the hypothesis, the quantitative approach is the most suitable choice for this study.

4.1 Instrument measures

The measurement items are derived from the existing BIM adoption studies. To ensure the validity and relevancy of items, face validity and content validity are performed. The five-point Likert scale is used to record responses to most of the items. The measurement items are provided in Appendix.

Relative advantage is measured in increased quality of information and communication (Mahalingam *et al.*, 2015) and visualization capabilities (Poirier *et al.*, 2014). BIM also offers reduced design errors, cost reduction, risk management, improved decision-making and enhanced market availability (Cemesova *et al.*, 2015). The user's experience with the system determines *compatibility*, which influences behavioural intentions to use the technology. The continuing use of technology is achievable if the system is compliant with the existing tools, processes and practices (Kim *et al.*, 2016; Seed, 2015; Son *et al.*, 2015). Finally, the *complexity* of BIM is measured in terms of difficulty in understanding BIM models, longer time to learn BIM, complex implementation process and complex user interfaces of BIM applications (Euisoon and Kim, 2016; Son *et al.*, 2015).

Top management support "when a senior management project sponsor/champion, the CEO and other senior managers devote time to review the supportive climate and resources for technology adoption" (Ahuja *et al.*, 2016). Also, in terms of providing facilitating conditions, management support promotes the system's usefulness among employees (Son *et al.*, 2015). *Organizational readiness* includes providing training to BIM users and hiring BIM service providers to smooth the functioning of BIM applications (Sodangi *et al.*, 2018). It is measured in the form of product-based, process-based and full maturity (Kassem and Succar, 2017). *Financial constraints* are measured in terms of the cost of applications, training cost and upfront implementation cost. BIM applications require a high initial set-up cost, application cost, environment set-up cost (Ahuja *et al.*, 2016) and additional BIM services cost (Koo *et al.*, 2017). *Uncertainty* is measured in privacy issues, security, risk of an investment, lack of data ownership and uncertainty in data (Latiffi and Hua, 2017).

Competitive pressure is measured in terms of peer organizations' competitiveness by early identification of cost estimation, material supplies required, labour cost estimation (Mohsenijam and Lu, 2016) and readjustments of business processes (Song *et al.*, 2017). The items for competitive pressure include good reputations in the industry, benefits gained using BIM, demand from customers and external actors' support. *Government support* items to measure include BIM mandated by the government and its role in promoting technology. Another item is tax rebates, providing a national standard for BIM adoption and promoting BIM training and education (Dong and Martin, 2017). *Regulatory support* is measured in terms of BIM recognition as industry-standard by regulatory bodies, BIM promotion in construction projects, propagation of the value of BIM in projects and BIM mandate within organizations.

Technical interoperability is measured in terms of exchanging information among BIM systems and the availability of exchange standards. Other items include the integration of BIM with existing systems and the inter-compatibility of BIM applications. *Organizational interoperability* is measured in organizations' BIM vision and mission, BIM roles in organizations, propagation of BIM at operational levels and defining BIM champions. The *semantic interoperability* measurement items include defining coordination processes, enabling interactive communication among various stakeholders, managing information flow and integrating reuse procedures of BIM-related information (Muller *et al.*, 2017). *Legal interoperability* is measured in terms of the availability of a legal framework for data ownership (Jiang *et al.*, 2017), contractual issues, BIM process standardization, compensation and insurance (Chong and Wang, 2016), intellectual property and specifying professional liabilities. *BIM adoption* is measured in BIM use in organizations, BIM implementation in construction projects and BIM users' capability.

4.2 Instrument validation

To ensure the validity and relevancy of items, face validity and content validity are performed. Face validity is done by sending items to two lecturers having research areas on technology adoption. The feedback received has been used to improve the questionnaire for its readability. Three BIM experts with at least ten years of experience did the content validity. One of them is the BIM director in an AEC company located in Selangor, Malaysia. The rest of the experts are from academia and work on BIM projects in collaboration with the industry. The pool of questionnaire items has been provided to the expert to decide the most relevant items related to each factor. Later on, the questionnaire has been revised according to the feedback provided by experts. A pilot study consisting of 30 respondents from AEC practitioners has been performed to enhance the instrument's accuracy and reliability. Based on the pilot test findings, some items have been updated and removed. The registered AEC companies' list is obtained from the CIDB website. A total of eight thousand AEC firms are registered with CIDB. A purposive sample is a non-probability sample that is selected based on the characteristics of a population and the objective of the study. The purposive sampling method was adopted to select 1,200 firms. After the revised instrument has been sent to 1,200 AEC organizations, 505 valid answers for further analysis of the data are kept.

4.3 Data collection

The data collection is done to form AEC firms in Malaysia. The majority of the firms are located in three cities, including Kuala Lumpur, Selangor and Johor Bahru. These cities are considered more developed and well planned, and most construction companies have established their offices. The companies' correspondence information is obtained from the CIDB and myBIM portals. CIDB is a government body that is responsible for looking after activities to promote digital construction. The AEC professionals from companies have been invited via sending emails and social networking channels. Google forms link has been forwarded to participants to get feedback.

4.4 Data analysis

A descriptive analysis of the data summarizes frequency distributions to determine the population's effective sample distribution. In addition, a missing data analysis has been performed using an average method to classify data missing from the survey. Two separate software applications, SmartPLS 3.0 and SPSS 25, have been used for survey data processing. Descriptive analysis and initial data screening for outliers and normality have been conducted using SPSS. This research study used the partial least square (PLS) technique of structural equation modelling to evaluate structural relationships. The model analysis process in SmartPLS has two steps. The first is assessing the measurement model, and the second is assessing the structural model (Hair *et al.*, 2013). The measurement model's estimate constructs reliability, convergent validity and discriminant validity.

Cronbach's alpha (CA) is a conventional criterion for internal consistency evaluation. The high CA value means that the importance and range of all items related to a single term are similar (Cronbach, 1951). An alternative measure of CA is composite reliability (CR) (Chin, 1998). The agreed standard value is 0.7 or above for CA and CR. A value of less than 0.60 shows a lack of consistency (Nunnally, 1994). The average variance extracted (AVE) is a widely applied convergent validity standard (Fornell and Larcker, 1981). The acceptable range of AVE values at 0.50 shows adequate convergent validity. Discriminant validity relates to the degree to which the construct is different from other constructs (Hair *et al.*, 2013). The discriminant validity assessment includes assessing cross-loadings and the Fornell–Larcker (FL) criterion. The cross-loadings are calculated by combining every latent variable's component scores with all the other items (Chin, 1998). The FL criteria indicate that the square root (AVE) should be greater than its correlation (Fornell and Larcker, 1981). The structural model shows the relationships or paths between the variables. Structural model evaluation requires evaluating the relationship between structures in the model. The assessment of the structural model consists of assessing path coefficients (b-values) and probability (p-values).

5. Results

This section discusses demographic analysis and the results of the measurement model and the structural model.

5.1 Respondent's demographic

The respondent's profiles are shown in Table 4. The analysis shows the highest response rate of 36% from architects, showing an interest in BIM adoption. The second-highest class of respondents belongs to engineers, with a 33.3% response rate. Quantity surveyors make up the next 12.5% of participants. Consultants and contractors account for 5.9% and 7.7%, respectively. Eventually, the least involvement from the client is recorded. Over 50% of respondents have a minimum experience of five years. About 61% of the companies are small and medium in size. Also, more than half of the companies are private, and one-quarter are public companies.

5.2 Measurement model

Scale reliability, discriminant validity and convergent validity are evaluated as part of the measurement model. The reliability is measured using CA and CR (Hair *et al.*, 2014). Table 5 shows that CR and CA are both greater than 0.70, as suggested by the research. AVE is used

Organization profile Demographic	Frequency	(%)
Designation		
Architect	182	36.0
Client	23	4.6
Consultant	30	5.9
Contractor	39	7.7
Engineer	168	33.3
Quantity surveyor	63	12.5
Gender		
Female	176	34.9
Male	329	65.1
Age		
20–25 years	135	26.7
25–35 years	297	58.8
35–45 years	54	10.7
Above 45 years	19	3.8
Experience		
<1 year	60	11.9
1–5 years	281	55.6
6–10 years	94	18.6
11–15 years	41	8.1
16–20 years	15	3.0
21–25 years	10	2.0
above 25 years	4	0.8
Project type		
Private	303	60.0
Private and Public	78	15.4
Public/Government	124	24.6
Organization size		
>100	198	39.2
1–10	81	16.0
11–25	82	16.2
26–50	75	14.9
51–100	69	13.7

Table 4. Demographic information of respondents

Table 5.
Construct reliability, convergent validity and discriminant validity

Construct	CA	CR	AVE	FL	Item loadings			
Government support	0.836	0.832	0.563	0.751	GS1	0.955	GS3	0.587
					GS2	0.625	GS4	0.777
Organizational readiness	0.822	0.895	0.74	0.889	OR1	0.783	OR3	0.883
					OR2	0.909		
Competitive pressure	0.889	0.914	0.726	0.835	CP1	0.852	CP3	0.825
					CP2	0.857	CP4	0.874
Compatibility	0.855	0.902	0.698	0.797	C1	0.785	C3	0.862
					C2	0.893	C4	0.796
Legal interoperability	0.896	0.924	0.753	0.712	LI1	0.803	LI3	0.92
					LI2	0.837	LI4	0.906
Organizational interoperability	0.912	0.938	0.791	0.868	OI1	0.888	OI3	0.912
					OI2	0.901	OI4	0.854
Complexity	0.69	0.802	0.507	0.852	BC1	0.708	BC3	0.844
					BC2	0.645	BC4	0.635
Relative advantage	0.821	0.886	0.722	0.861	RA1	0.923	RA3	0.856
					RA2	0.763		
Regulatory support	0.894	0.926	0.757	0.851	RS1	0.851	RS3	0.874
					RS2	0.898	RS4	0.857
Semantic interoperability	0.917	0.94	0.796	0.872	SI1	0.918	SI3	0.882
					SI2	0.866	SI4	0.901
Technical interoperability	0.83	0.886	0.661	0.892	TI1	0.842	TI3	0.805
					TI2	0.847	TI4	0.756
Top management support	0.926	0.953	0.87	0.813	TS1	0.94	TS3	0.913
					TS2	0.945		
Uncertainty	0.717	0.84	0.636	0.933	UN2	0.769	UN4	0.777
					UN3	0.845		
Financial constraints	0.731	0.881	0.788	0.798	FC2	0.886	FC3	0.889
BIM adoption	0.711	0.839	0.635	0.888	A1	0.765	A3	0.848
					A2	0.774		

to determine convergent validity, and the required level of 0.50 is met. The item loadings of all the constructs are above 0.70. Finally, discriminant validity is measured using FL criteria and cross-loadings. The comparison of square roots of (AVE) given in Table 5 shows higher values concerning constructs' correlation. Similarly, the comparison of loadings and cross-loadings, as shown in Table 5, shows greater loading values and satisfies the discriminant validity threshold. The findings show that all the constructs have adequate internal consistency reliability, which means that all the constructs' indicators are reliable. Also, the measurement model fulfils the discriminant validity required for a stable model.

5.3 Structural model: hypothesis testing

Table 6 shows the probability (p-values) and path coefficient (b-values) of hypothesis testing results. Regarding the hypothesis significance, all hypotheses of this study are significant except *H3*, *H8* and *H13*. The revised model based on statistical findings is shown in Figure 3. The study's findings indicate that Top management support, relative advantage, government support, organizational readiness and regulation support are determinants of BIM adoption. On the other hand, complexity, financial constraints, lack of technical interoperability, semantic interoperability, organizational interoperability and uncertainty are barriers to BIM adoption. However, compatibility, competitive pressure and legal interoperability do not affect BIM adoption

Construct	*b*-values	*p*-values
Organizational Readiness → BIM Adoption	0.4468	0. 0000
Semantic Interoperability → BIM Adoption	–0.3654	0. 0000
Relative Advantage → BIM Adoption	0.1955	0. 0000
Uncertainty → BIM Adoption	–0.2009	0.0001
Government support → BIM Adoption	0.1630	0.0028
Top Management support → BIM Adoption	0.1394	0.0002
Organizational Interoperability → BIM Adoption	–0.1957	0.0314
Technical Interoperability → BIM Adoption	–0.1048	0.0025
Regulation Support → BIM Adoption	0.0804	0.0334
Complexity → BIM Adoption	–0.0700	0.0348
Financial Constraints → BIM Adoption	–0.0674	0.0441
Legal Interoperability → BIM Adoption	0.03872	0.2081
Competitive Pressure → BIM Adoption	0.0264	0.3131
Compatibility → BIM Adoption	0.0138	0.3524

Table 6. Hypothesis testing results

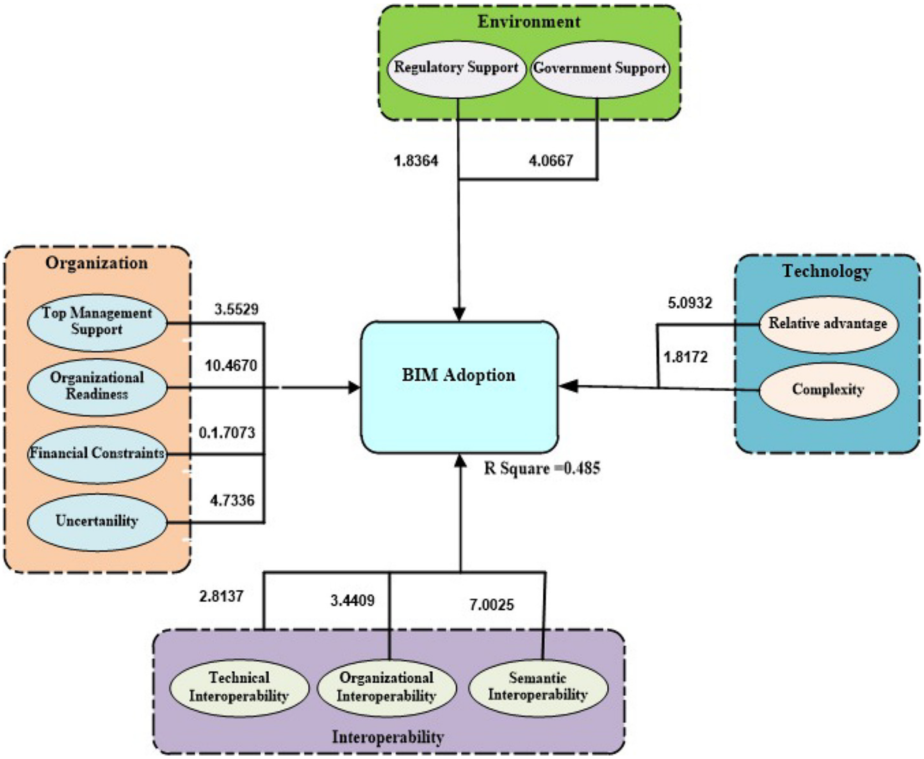

Figure 3. Revised BIM adoption model

5.3.1 Technology factors. The findings show that relative advantage is the influencing factor on BIM adoption. The AEC investors believe that BIM is a valuable technology that manages business operations and construction activities (Ahuja *et al.*, 2016, 2018a, 2018b; Chen *et al.*, 2019). Additionally, complexity is negatively associated with BIM adoption and represents a major barrier. Therefore, the technology that is easier to use and manage is more likely to be widely adopted. Similarly, learning time for a complex technology is relatively long, hence, inhibiting technology adoption. The AEC industry considers BIM complex to use and learn. Furthermore, surprisingly, compatibility does not affect BIM adoption (Ahuja *et al.*, 2016; Chen *et al.*, 2019). The result implies that compatibility seems to have little bearing on BIM adoption. It seems that the AEC would find it inconsistent with their current work procedures and practices. However, BIM is regarded as a quantum leap technology that would transform the building industry's business strategies.

5.3.2 Organizational factors. The findings of the study suggest that organizational readiness is a key factor in BIM adoption. Firms that have the necessary IT infrastructures and internal skills to implement BIM are more likely to adopt BIM. The additional benefit of an organization's internal expertise is that it can test the software before implementing it, assuring them in their adoption decision. The top management support has a positive influence on BIM adoption found in this study. Executives and higher management generally decide the adoption of technology. Hence, organizations where management shows their support and provides necessary resources are more likely to adopt BIM. The cost of BIM adoption was found to be negatively correlated in this study. The cost of BIM technology, maintenance costs and implementation costs are all financial restrictions (Xu *et al.*, 2014; Ahuja *et al.*, 2016). Construction stakeholders are reluctant to invest in technologies with high costs and risks. Every discipline in the building industry should have a BIM team. Every team designs its model. In case of any change at later stages, all the teams update the model. It incurs costs and running expenses in projects. Uncertainty is the perceived risk associated with any technology. This study found uncertainty is negatively associated with BIM adoption. AEC professionals are uncertain about the privacy and security of data when models are exchanged among multiple parties.

5.3.3 Environmental factors. According to the analysis, there appears to be no pressure from competing organizations. Another hypothesis is that AEC stakeholders are holding off on adopting BIM in their businesses until they see particular improvements and benefits from pioneer BIM adopters. On the other hand, competitive pressure has a low prevalence in small and medium firms as they are least associated with technological contributions and completive advantage. Regulatory support from professional bodies forms desirable behaviour regarding technology adoption in an organization. It suggests that regulatory authorities demand and support BIM. Government support has been found as another driver for BIM adoption in Malaysia. Comparatively, in other countries, like Singapore and UK, government support is a driving factor in BIM adoption (SBCA, 2012; UKBIMA, 2016). Also, most of the respondents reported no tax rebates, subsidies or other government incentives for technology adoption. It seems as if the Malaysian government is slow in addressing the technology needs of the construction industry. Another issue is the lack of government support for legal contracts.

5.3.4 Interoperability factors. Lack of technical interoperability is one of the most critical variables affecting BIM adoption. The findings of this study are consistent with existing studies (Aksenova *et al.*, 2018; Alreshidi *et al.*, 2016; Lee *et al.*, 2016; Xu *et al.*, 2014). This software's inconsistent models cause conflicts among different stakeholders involved in a construction project (Xu *et al.*, 2014). In a CPDS, team members hesitate and are unlikely to accept the risk resulting from contradictory models and practices that have dramatically reduced the importance of BIM. The most critical variable affecting the adoption of BIM is organizational interoperability. This study found a lack of organizational interoperability is negatively associated with BIM adoption. Organizational interoperability is much more difficult to achieve than technical interoperability. One of the main concerns regarding organizational interoperability is how the organization's data model is central or decentralized. As most AEC firms are independent, corporation between different AEC companies is often challenging. It can also be a problem to inspire various companies to do some horizontal cooperation (Merschbrock and Nordahl-Rolfsen, 2016). Semantic interoperability issues include the absence of a data collection methodology relating to facilities management, poor synchronization of information, insufficient data categorization and inconsistent naming conventions (Farghaly *et al.*, 2018).

The lack of semantic interoperability is found to have a negative effect on BIM adoption. The fragmented nature of data exchange standards in use is a cause of the poor semantic interoperability of BIM systems. Surprisingly, this study found no relationship between legal interoperability. It seems that Malaysian construction firms are working independently or rarely have collaborative projects. Another reason may be that they have trust and faith in peer firms or rarely have faced legal issues. However, the findings of existing studies show that the lack of legal interoperability in a CPDS is a significant issue (Englund and Grönlund, 2018). There is a possibility of legal problems related to model ownership and intellectual property rights in a joint project.

6. Conclusions

BIM is an interesting area of study because of its applications in the AEC and related fields. Assessing the BIM adoption process and its dynamics is vital to both policymakers and adopters at the individual and organizational levels. Several factors influence BIM adoption, such as lack of industry readiness, lack of awareness, lack of government initiatives and resistance to change. A substantial impediment to BIM adoption often cited is data interoperability. Other facets of interoperability got limited attention. This study investigates the effect of interoperability factors on BIM adoption and develops a comprehensive BIM adoption model. The study's contribution is to combine and categorize the factors into four dimensions and explain their relationship. The proposed model is theoretically based on EIF and TOE. The study's findings indicate that Top management support, relative advantage, government support, organizational readiness and regulation support are determinants of BIM adoption. On the other hand, complexity, financial constraints, lack of technical interoperability, semantic interoperability, organizational interoperability and uncertainty are barriers to BIM adoption. However, compatibility, competitive pressure and legal interoperability do not affect BIM adoption. Finally, this research offers recommendations containing the essential technological, organizational, environmental and interoperability factors that the AEC industry can address to enhance BIM adoption. This research study identified critical factors in the interoperability dimension that should be considered for the BIM domain's interoperability. These identified factors will help the policymakers to develop a roadmap to overcome the barriers to interoperability.

The significance of this study is twofold. In terms of theoretical contribution, this study combines elements from the TOE and EIF, hence, providing an integrated approach to address BIM adoption issues. Existing studies use traditional adoption theories such as TAM, Institutional theory and UTAUT to address adoption issues. However, this study contributes to a new model for testing BIM adoption from multiple perspectives. Concerning the study's practical contributions, the identified cluster of BIM adoption factors can help decision makers conduct different analyses of the BIM adoption process and formulate adoption strategies by offering facts and observations within organizations and throughout the construction industry. Also, strategies are provided to successfully adopt BIM in organizations and enhance adoption among organizational and external environments.

Even though this research offers a detailed understanding of BIM adoption variables, it has limitations. The main is the selection of respondents, as data gathering is limited to big Malaysian cities. Future research should include an overall sample size that provides for firms from different Malaysia locations, including east Malaysia. To get a full picture of the adoption phenomenon, it is also a good idea to mix several theories and models. Researchers interested in technology adoption will benefit from this study, which will aid them in furthering their research into the BIM adoption field. This research assists practitioners and AEC firms tackle the identified issues in evaluating and enhancing BIM adoption.

6.1 Recommendations for technology factors

The findings show that relative advantage is the influencing factor on BIM adoption. The BIM developer companies are recommended to improve BIM software features to accommodate all AEC stakeholders. Additionally, complexity is negatively associated with BIM adoption and represents a significant barrier. Similarly, learning time for a complex technology is relatively long, inhibiting technology adoption. The BIM developer companies are recommended to reduce BIM software's complexity to make it more user-friendly and easy to understand and apply. Compatibility refers to the integration of old and new technologies, as well as its impact on user perceptions of system utility. The AEC might think BIM is incompatible with their existing work procedure and methods. The BIM developer companies are recommended to address compatibility issues of BIM software to make it more compatible with the current infrastructure. Uncertainty is the perceived risk associated with any technology. The professionals are uncertain about the privacy and security of data when models are exchanged among multiple parties. Therefore, BIM development companies are recommended to address the protection concerns, IT risks and privacy because of their openness and pervasiveness.

6.2 Recommendations for organizational factors

The findings of the study suggest that organizational readiness is a key factor in BIM adoption. Firms that have the necessary IT infrastructures and internal skills to implement BIM are more likely to adopt BIM. Therefore, AEC firms are recommended to improve staff competencies with BIM training programs. Also, the budgeted allocation for the purchase and implementation of new BIM products is recommended. The top management support positively influences BIM adoption found in this study. At medium and large-scale levels, the AEC organizations have several hierarchical teams, including top management, middle management and executive bodies. Executives and higher management generally decide the adoption of technology. Hence, the top management should show its support and provide the necessary resources to adopt BIM. The cost of initial hardware, software set-up, maintenance cost and training cost is the greatest financial barrier to BIM adoption. However, such economic challenges have more bearing on small companies than on large organizations. Therefore, the BIM development companies are suggested to reduce the BIM software cost to be accessible for small and medium companies. BIM companies should also provide BIM training at reasonable prices to facilitate many new users.

6.3 Recommendations for environmental factors

The AEC stakeholders are holding off on adopting BIM in their businesses until they see particular improvements and benefits from pioneer BIM adopters. Competitors may not be conscious of competition from other firms. Technology leaders play a vital role in adopting any technology by showing rewards and benefits from technology and persuading other competitors to adopt BIM. On the other hand, competitive pressure has a low prevalence in small and medium firms as they are least associated with technological contributions and competitive advantage. Regulatory support from professional bodies forms desirable behaviour regarding technology adoption in an organization. Therefore, it is recommended that the Malaysian construction industry, CIDB, Pertubuhan Akitek Malaysia and the quantity surveys (Malaysia) board provide regulation support and work as a deriving force for BIM adoption. Government support has been found as another driver for BIM adoption in Malaysia. The government should also provide tax rebates, subsidies or other government incentives for technology adoption. Moreover, government regulations need to be created because the existing rules do not address the industry's present and future requirements.

6.4 Recommendations for interoperability factors

Lack of technical interoperability is one of the most critical factors affecting BIM adoption. The BIM development companies should support open standards like IFC and openBIM to seamlessly exchange and integrate BIM applications. Similarly, BIM applications should be compatible with firms' existing hardware facilities. Standardization of protocols should be made to avoid data exchange issues. To work at the corporate level, organizational interoperability is essential for BIM-based companies. The most critical factor affecting the adoption of BIM is the lack of organizational interoperability. As most AEC firms are independent, corporation between different AEC companies is often challenging. BIM's vision and mission should be defined in every AEC organization. The organizational roles regarding BIM should be decided, and organizations' positions must be determined. Semantic interoperability issues include the absence of a data collection methodology relating to facilities management, poor synchronization of information, insufficient data categorization and inconsistent naming conventions. The fragmented nature of data exchange standards should be standardized for the semantic interoperability of BIM systems. Also, the interaction between information systems and their environments should be open. Resolving legal and contractual issues is essential when collaborating on joint projects to eliminate legal risks. There is a possibility of legal problems related to model ownership and intellectual property rights in a collaborative project. Similarly, fixing responsibility in case of any clash is a matter of concern. Therefore, the issues mentioned above should be tackled to attain legal interoperability.

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Appendix

Table A1. Questionnaire items used in the current study

Factor	Items to measure
Relative advantage	(1) Using the BIM model improves the quality of work and increases our productivity (Ahuja *et al.*, 2016)
	(2) Using BIM, overall construction cost is reduced (Kim and Yu, 2016)
	(3) BIM provides more control and coordination of construction activities (Ahuja *et al.*, 2016)
Compatibility	(1) BIM process is consistent with our beliefs and values (Ahuja *et al.*, 2016)
	(2) BIM applicability to existing processes is without change (Kim and Yu, 2016)
	(3) Attitude towards BIM in our organization has always been favourable (Ahuja *et al.*, 2016)
	(4) BIM is compatible with our existing practice (Ahuja *et al.*, 2016)
Complexity	(1) We believe that BIM-related software is complex to use (Ahuja *et al.*, 2016)
	(2) We believe that learning BIM is not easy (Kim and Yu, 2016)
	(3) We believe that BIM implementation is a complex process (Ahuja *et al.*, 2016)
	(4) Problem with user-friendliness exist in BIM (Bosch-Sijtsema *et al.*, 2017)
Competitive pressure	(1) Peer projects that have adopted BIM have gained good reputations in the industry (Cao *et al.*, 2014)
	(2) Peer projects that have adopted BIM are perceived favourably by others in the industry (Cao *et al.*, 2014)
	(3) Peer projects that have adopted BIM have benefitted greatly (Cao *et al.*, 2014)
	(4) The overall operational practices in the industry pressure us to adopt BIM (Bosch-Sijtsema *et al.*, 2017)
Government support	(1) The government provide tax rebate for the adoption of BIM technology (Dong and Martin, 2017)
	(2) The government provides subsidies for the purchase of BIM software's for small and medium enterprises (Dong and Martin, 2017)
	(3) The government promotes BIM education and is providing training at the national level (Dong and Martin, 2017)
Regulatory support	(1) The government requires our project to use BIM (Cao *et al.*, 2014)
	(2) The government has defined the national standard for BIM adoption (Dong and Martin, 2017)
	(3) Government agencies are active in setting up BIM adoption policies and regulations (Lee *et al.*, 2015)
	(4) Industry associations require our project to use BIM (Cao *et al.*, 2014)
	(5) Industry associations have effectively communicated their support for BIM (Cao *et al.*, 2014)

(*continued*)

Factor	Items to measure
Top management support	(1) Top management is interested in the implementation of BIM (Ahuja *et al.*, 2016)
	(2) The top management has effectively communicated its support for BIM (Ahuja *et al.*, 2016)
	(3) Management is aware of the benefits that can be achieved with the use of BIM systems (Park *et al.*, 2012)
Organizational readiness	(1) Our employees are generally aware of the BIM functions (Ahuja *et al.*, 2016)
	(2) Our firm has highly specialized or knowledgeable personnel for the BIM process and implementation (Ahuja *et al.*, 2016)
	(3) We have sufficient financial resources to adopt BIM. (Chen *et al.*, 2019)
Financial constraints	(1) BIM adoption has high set-up costs, running costs and maintenance costs (Ahuja *et al.*, 2016)
	(2) BIM adoption has high training costs (Ahuja *et al.*, 2016)
	(3) Lead time for full-scale BIM implementation is relatively long (Ahuja *et al.*, 2016)
Uncertainty	(1) In our opinion, BIMcloud providers' servers and data centres are not secure (Abanda and Mzyece, 2018)
	(2) In our opinion, BIMcloud providers would be unsafe to maintain the confidentiality of our data (Abanda and Mzyece, 2018)
	(3) In our opinion, BIMcloud provides an insecure service (Abanda and Mzyece, 2018)
	(4) Overall, there is a concern about the security of BIMcloud services (Abanda and Mzyece, 2018)
Technical interoperability	(1) It is easier to integrate BIM with other systems (Bosch-Sijtsema *et al.*, 2017)
	(2) Data exchange among BIM software and applications is easy. (Xu *et al.*, 2014)
	(3) Data exchange standards are widely available for BIM (Xu, Feng and Li, 2014)
	(4) BIM models generated by BIM software are free from any compatibility issues (Xu *et al.*, 2014)
Organizational interoperability	(1) BIM Goals and objectives in our organization are clearly defined (Wu *et al.*, 2017)
	(2) BIM products and services are evaluated continuously, and feedback loops promote continuous improvement (Wu *et al.*, 2017)
	(3) Arrangement of BIM-related duties and roles are formally implemented to exchange BIM-related information (Wu *et al.*, 2017)
	(4) The functions of BIM champions are formalized in our organization to support intra and inter-organizational information needs (Succar and Sher, 2014)

(*continued*)

Table A1.

Factor	Items to measure
Semantic interoperability	(1) BIM data from local and external systems can be combined and processed identically and collectively (Alreshidi *et al.*, 2017) (2) BIM data can be processed meaningfully without the additional work of data transformation and knowledge management (Alreshidi *et al.*, 2017) (3) BIM helps to reduce coordination errors in a project to a large extent by establishing a common language for widely referenced processes (Farghaly *et al.*, 2017) (4) Parts of data models can be individually mapped and interpreted meaningfully among BIM systems (Farghaly *et al.*, 2017)
Legal interoperability	(1) There is sufficient development of contracts for BIM-related risk allocation in BIM-enabled projects (Fan *et al.*, 2018) (2) It is easier to determine intellectual property rights on a multi-stakeholder project (Fan *et al.*, 2018) (3) It is easy to determine who should own the BIM process in an integrated project delivery system (Fan *et al.*, 2018) (4) There are sufficient contractual arrangements to protect the BIM model's private data from loss and misuse (Fan *et al.*, 2018)
BIM adoption	(1) Did your company adopt BIM? (Chen *et al.*, 2019) (2) Did your company buy BIM software? (Chen *et al.*, 2019) (3) Did your company implement a BIM service? (Chen *et al.*, 2019)

Table A1.

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