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Determining building information modeling effectiveness

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ABSTRACT

Building Information Modeling (BIM) is a promising development that can address the inherited inefficiencies in construction. This research aims to develop a framework for assessing BIM effectiveness. Following an extensive literature review and expert opinions, the proposed framework was generated with a total of seven constructs. Structural Equation Modeling (SEM) was used to validate the proposed framework and test the research hypotheses based on 172 responses collected from 107 construction projects. The results revealed that BIM effectiveness is mainly governed by project- and company-based factors; where industry-based factors have indirect influences. Besides, BIM effectiveness drives higher process effectiveness, which in turn generates project- and company-related benefits. This research has developed an interactive framework that could be used to collect and analyze data from other countries to enable comparison of findings. Construction practitioners and policy-makers can benefit from the recommended strategies to enhance BIM effectiveness at project, company, and industry levels.

1. Introduction

Technological advancement can be measured by means of improvements in the efficiency of production methods or the raw material consumption. Enhanced productivity decreases costs, increases profits, and improves the standard of life by making goods and services affordable. Unfortunately, construction industry has achieved very little technological advancement [1]. The increasing competition in the international construction market puts pressure on construction companies to enhance their performances [2]. In this respect, Building Information Modeling (BIM) is considered a great opportunity for the companies to sustain their competitiveness globally.

BIM is considered a new work method rather than just an improvement in the construction process. BIM ensures that a single model can include and coordinate construction documents, visualization, material quantities, cost estimates, construction sequencing, scheduling, and fabrication [3]. Designers can make iterations, simulations, and tests on many aspects of the construction process before the actual construction starts. Correction of inaccuracies virtually prior to construction provides material and time savings [4]. Similarly, construction managers and supervisors can simulate the construction process before they commit to the labor and materials. Product and process alternatives can be explored, parts can be changed, and the construction procedures can be adapted in advance. Being able to perform all the activities continuously helps them to deal with the unexpected situations before they emerge [5].

BIM is a relatively new concept for the construction industry. Even though the BIM concept goes back to 1970s [6], BIM implementation started in the construction industry in 2000 [7]. Investigation of BIM implementation in construction projects has been a trending research topic. A number of studies have analyzed BIM implementation from various perspectives such as investigation of the success parameters ([8–10]), evaluation of the performance ([11–13]), and realization of the outcomes ([14–16]). However, there are few studies conducted to analyze BIM implementation by considering these perspectives as a whole.

This research aims to develop a comprehensive BIM effectiveness framework. The framework is mainly composed of the determinants (project-, company-, and industry-based factors), measurements (BIM and process effectiveness criteria), and outcomes (project- and company-related benefits). Structural Equation Modeling (SEM) is the statistical analysis technique used to validate the framework and reveal the interactions between the constructs based on data collected through a questionnaire survey directed to BIM practitioners. The objectives of the research are to (i) develop an extensive BIM effectiveness framework, (ii) unveil the interactions between the constructs, (iii) prioritize

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the factors under each construct, and (iv) propose a roadmap to promote BIM implementation.

The research proposes a novel conceptual framework to systematically assess the effectiveness of BIM implementation within the context of country characteristics. The main difference and value of the study lies in the fact that the model incorporates the interrelated nature of the parameters under investigation. Besides, the recommended strategies are distinguished at three different levels (project, company, and industry) as well as different stakeholders (construction companies, government bodies, and non-profit organizations). Findings of the research and the recommendations can help devise mechanisms to diffuse BIM use in the construction projects and improve the effectiveness of BIM-enabled project management practices.

The paper consists of six sections. The second section summarizes previous studies focusing on BIM implementation from various perspectives. The methodology (development of the framework, data collection, SEM analysis, and roadmap development) is presented in the third section. In the fourth section, the results of the analysis (respondent profiles, path coefficients, reliability and validity tests, and factor loadings) are shown and the roadmap is introduced. The fifth section discusses the interactions between the constructs, the most significant factors, and the proposed roadmap. In the conclusion section, major observations are indicated, recommendations are provided, limitations are expressed, and contribution to the body of knowledge is emphasized.

2. Research background

BIM is considered a ground-breaking technological advancement in the construction industry. It has therefore been one of the most attractive research fields, especially in the last decade, when the number of applications has significantly increased all over the world. There is an increasing trend in the academia to conduct studies on BIM. Its implementation and adoption have been reported as the most trending topics [17]. Additionally, it has been analyzed from various perspectives including identification of BIM success determinants, evaluation of BIM performance, and realization of project benefits.

2.1. Determinants of BIM success

Factors that influence the effectiveness of the BIM implementation process have been discussed by several researchers. These factors have frequently been called the critical success/risk factors or key performance indicators. Researchers have created a list of factors based on literature review or interviews with experts, categorized the factors, evaluated their significance, determined the critical ones, and developed strategies to increase the possibility of project success.

Rogers et al. [18] worked on BIM adoption among Malaysian engineering consulting firms. They collected primary data from questionnaire survey and focus group interview. They (i) explored the perceptions, main barriers, governmental support, and intentions; and (ii) identified the key drivers. Lack of qualified personnel and governmental support were reported as the main obstacles. Main drivers to adopt BIM within two years were stated as the market demands and competitive advantage. Ding et al. [19] explored the key factors for BIM adoption by architects in China. A structural equation model was applied based on survey data obtained from design firms in Shenzehn, China. Motivation, BIM capability, and technical insufficiencies of BIM were the most significant factors. The least important ones were stated as the management support and knowledge structure.

Lee et al. [20] demonstrated the positive influence of trust on the BIM performance of construction projects through proposing an integrative trust-based functional contracting model. They encouraged the construction industry to think beyond the conventional engineering, procurement, and construction contract setting for achieving a much more effective BIM use. Liao and Ai Lin Teo [21] proposed an organizational change framework to identify the hindrances and drivers of BIM implementation in people management. Investigation of previous studies revealed 24 hindrances and 13 drivers. Analysis of a questionnaire survey of 84 experts in Singapore and post-survey interviews refined the factors in the list and resulted in 22 hindrances and 12 drivers.

Tan et al. [10] conducted a study to identify the barriers specifically for the China's prefabricated construction and discover the interrelations between them by using interpretive structural modeling. Greatest obstacles were determined as lack of research in the country on BIM and absence of standards/domestic tools. A three-level strategy was proposed to facilitate implementation of BIM. Chen et al. [22] discussed BIM adoption in construction firms within the context of Chinese construction industry. They developed technology-organization-environment framework to create a research model and make evaluation. Two different data sets were collected from consulting and construction firms. Relative advantage of BIM was specified as the main enabler and complexity was regarded as an inhibiter. It was also noticed that younger firms had a greater tendency to implement BIM.

2.2. Assessing the BIM performance

Various studies have focused on BIM performance assessment and its influence on the construction process. The BIM performance has usually been assessed based on previously defined BIM implementation levels or by implementing performing assessment models. Contributions of effective BIM implementation to the construction process have been investigated in great numbers of case studies and a positive influence has frequently been emphasized.

Poirier et al. [23] assessed the BIM performance of a small mechanical contracting enterprise by conducting a case study over 2-year period. The BIM implementation performance was assessed using cost predictability, scope predictability, productivity indicator predictability, schedule predictability, and project quality. Won and Lee [12] studied the application of success level assessment model (SLAM) for BIM projects. They tested the validity of SLAM BIM by applying it to two construction projects. They collected and analyzed the data of design errors, response time, schedule, change orders, and return-on-investment. Importance of sharing SLAM key performance indicators and data collection methods in early project phases was highlighted.

Chang et al. [24] investigated how implementation of BIM could influence the construction process through enhancing the acceptability of integrated project delivery. They used structural equation modeling to analyze data obtained from 145 BIM-enabled projects in China. It was reported that enhancing communication and encouraging supply change incentives could make the BIM implementation positively affect the construction process. Ghaffarianhoseini et al. [13] discussed the widespread benefits of BIM and current level of uptake. They handled the issue from technical, knowledge management, standardization, diversity, integration, economic, planning, building life cycle, and decision support perspectives. It was suggested that the level of BIM comprehension and adoption could be highly associated with the size of a construction firm.

Smits et al. [25] conducted a survey of 890 Dutch construction professionals to explore their perceptions regarding the impact of BIM maturity on project performance. A limited influence of BIM maturity was observed on project performance. Maturity of BIM implementation strategy was noted to be the only determinant of time, cost, and quality performance. Liu et al. [26] studied how BIM might affect the design and construction process through enabling collaboration. BIM collaboration was reported to be influenced by following concepts: IT capacity, technology management, attitude and behavior, role-taking, trust, communication, leadership, and experience. Effects of BIM on the construction process were assessed under three categories, namely technology, people, and process.

2.3. Benefits of BIM implementation

A number of studies have targeted realization and quantification of the project benefits obtained. Project benefits have mostly been discussed in terms of monetary values. Value addition to the project and reduction in project costs have been highlighted. Monetary savings have been expressed as a percentage of total project cost. Several studies have also drawn attention to reduced project duration, quality improvements, and risk mitigation.

Lu et al. [14] aimed to measure costs/benefits of BIM implementation through demystification of time-effort distribution curves of construction projects. Comparison of two housing projects (one with BIM) indicated more effort input at the design stage, but lower costs at the building stage. The ultimate contribution of BIM implementation to the project was 6.92% reduction in costs. Zhou et al. [27] formulated a framework to evaluate project-level BIM benefits from the viewpoint of various stakeholders and explained the methods for maximizing the benefits for each stakeholder. The benefits were investigated from the operational, organizational, managerial, and strategic perspectives. Methods of BIM implementation were expressed in order to maximize the benefits for each stakeholder.

Fadeyi [15] demonstrated the value addition of BIM to the project through decreasing fragmentation among project members at each building delivery stage. It was emphasized that BIM could provide a virtual repository allowing easy access and information sharing. The integrated environment enabled by BIM for construction professionals was shown to add value to the project. Olawumi and Chan [16] used Delphi survey technique to identify and prioritize 36 perceived benefits of integrating BIM in construction projects. The derived data was analyzed by statistical tools and interrater agreement statics was used to validate the consensus reached by the expert panel. Enhancements in quality, building simulation, and product design were specified as the top benefits.

Even though there have been great number of studies investigating the determinants of BIM implementation, BIM & construction process performances, and the benefits obtained; few studies have considered them as a whole and investigated the interactions among them. This study offers a systematic approach to develop an interactive and extensive framework that focuses on the entire BIM implementation process rather than concentrating on a single component. The need for a comprehensive and systematic approach was also emphasized by Yalcinkaya and Singh [17]. The research contributes to the body of knowledge through proposing a novel conceptual framework to systematically assess the effectiveness of BIM implementation within the context of country characteristics.

3. Research methodology

The flow of the research methodology is presented in Fig. 1. The methodology is mainly composed of four phases: (i) preparation of the BIM effectiveness framework, (ii) conducting a questionnaire survey, (iii) structural equation modeling analysis, and (iv) roadmap proposal. In the first phase, the BIM effectiveness framework was generated. Constructs were defined and their interactions were specified through developing hypotheses. A literature survey was conducted to identify the underlying factors of each construct. The identified factors were either merged or removed to obtain a compact list. The second phase involved conducting a questionnaire survey. An online questionnaire survey was created by using google forms. The survey was directed to construction professionals with BIM experiences. Face-to-face interviews were performed to increase the response rate. SEM analysis was conducted in the third phase. The data was analyzed by using the commercially available software, namely IBM SPSS AMOS. The path coefficients were calculated. The validity of the model was ensured by the execution of content and construct validity tests. In the fourth phase, a roadmap was proposed. The results of the analysis were discussed. Meetings were organized with experts and strategies were formulated to promote BIM effectiveness. A roadmap including certain actions to be executed by various parties was presented.

3.1. BIM effectiveness framework

Fig. 2 shows the BIM effectiveness framework, its constructs, and their interactions. The framework comprises determinants, measurements, and outcomes. The determinants are the constructs that influence how effectively BIM is implemented throughout the project. There are three determinants, namely project-based factors, company-based factors, and industry-based factors. Measurements are the criteria that evaluate the level of effectiveness of both BIM implementation and the construction process. The outcomes represent the benefits obtained owing to the BIM implementation throughout the project. The benefits are considered both project-wise and company-wise.

The determinants include project-based factors, company-based factors, and industry-based factors. Project-based factors indicate the favorability of the project environment. For example, they might involve training given to the project personnel, BIM capability of the staff, and motivation to implement BIM. Company-based factors reveal the competencies of the company. Availability of key personnel, company experience in software programming/BIM, and investments are some examples considered in this construct. Industry-based factors demonstrate the maturity of the technology in the construction industry. Examples may involve availability of guidelines and protocols,

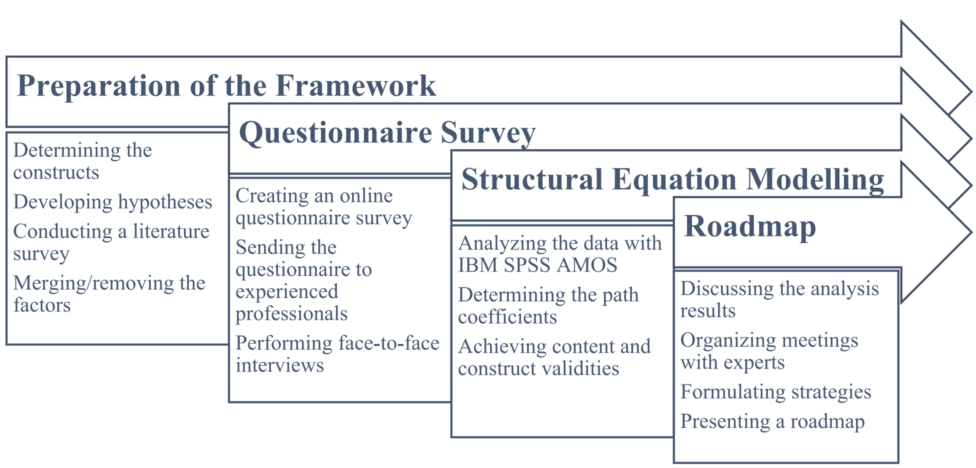

Fig. 1. Flow of research methodology.

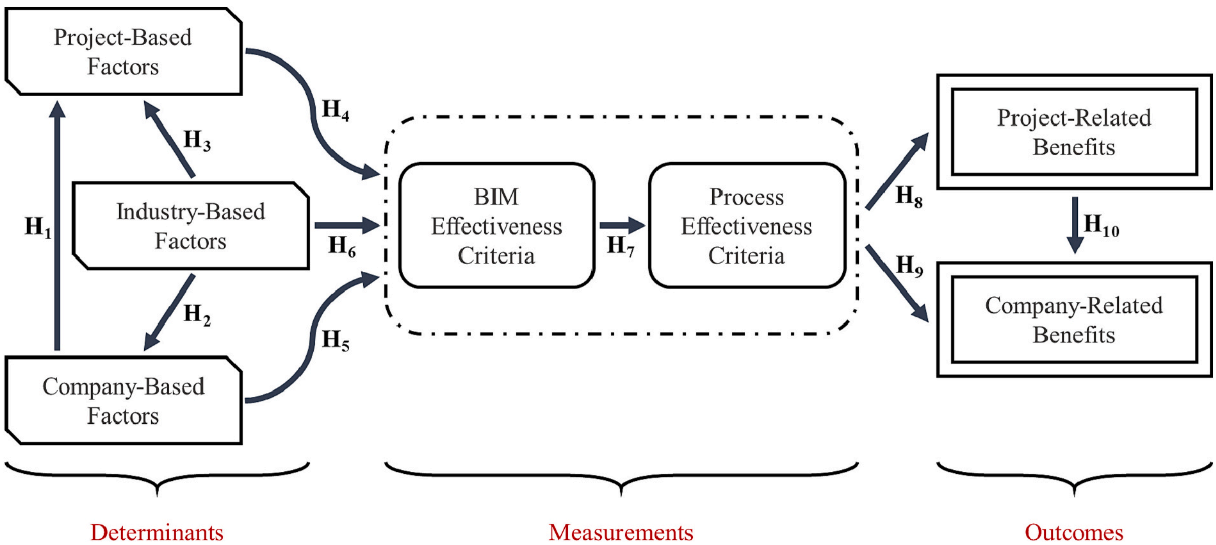

Fig. 2. BIM effectiveness framework.

interoperability level of software platform, and awareness within the industry.

Measurements incorporate criteria that measure the effectiveness of both BIM implementation and its influence on the construction process. Effectiveness of BIM implementation is measured via assessing the extent to which the BIM model is generated successfully. A successfully generated BIM model is expected to result in proper construction documents, accurate quantity survey, and advanced visualization. Thus, such factors are embedded in the BIM effectiveness criteria. The reflections of a well-established BIM model on the construction process are measured by the process effectiveness criteria. These criteria contain indicators of an effective construction process such as increase in labor productivity, improved coordination of disciplines, and enhanced communications between the project participants.

The outcomes are the project-wise and company-wise benefits realized by the virtue of the effective BIM implementation. While the project-related benefits represent the benefits obtained specifically for the project, company-related benefits stand for the contributions of BIM implementation to the company in the long run. Project-related benefits are evaluated in terms of the main features of projects such as time, cost, and quality. Company-related benefits, on the other hand, cover the enhancements in company characteristics like technology adoption, long-term profitability, and knowledge management.

3.1.1. Development of hypotheses

Hypotheses were developed to examine the interactions among the constructs. A total of ten hypotheses were constructed based on the relationships between the constructs and evidence from the literature. The hypotheses are explained as follows:

H1. Effectiveness of "company-based factors" has a direct and positive impact on "project-based factors".

Experienced and corporate companies are expected to create favorable project environment for implementing new technologies like BIM. These companies can accomplish a smooth project selection process in line with the strategic objectives and project environment [28]. They attempt to change the project environment in a positive way by training the project staff, recruiting specialists, and working with knowledgeable subcontractors.

H2. Effectiveness of "industry-based factors" has a direct and positive impact on "company-based factors".

Companies are expected to make greater investment in new technologies with the increasing maturity of the technology within the industry. The increasing awareness, availability of much capable software, and well-established guidelines and protocols may encourage companies to keep up pace with the technology. Ahmed [29] stated the suitability of the construction market as an important parameter for BIM implementation in construction companies.

H3. Effectiveness of "industry-based factors" has a direct and positive impact on "project-based factors".

The favorability of project conditions should depend on the maturity of the technology within industry. To clarify, a positive correlation might be assumed between the existence of BIM protocols and clarification of rights and responsibilities in the project, awareness of the technology within the industry and commitment to updating the model throughout the project, and so on. It should be noted that the construction industry is still in the early phases of BIM adoption [30].

H4. Effectiveness of "project-based factors" has a direct and positive impact on "BIM effectiveness criteria".

Effectiveness of BIM implementation might be influenced by the favorability of the project environment. A project with capable/committed participants and clarified responsibilities is expected to result in successful BIM implementation. Cao et al. [31] reported that implementation of BIM should be directly associated with the project characteristics.

H5. Effectiveness of "company-based factors" has a direct and positive impact on "BIM effectiveness criteria".

The context of a construction company shall contribute to the quality of the BIM process [32]. Innovative companies with flexible organizational structure are more likely to fluently execute the BIM process. The innovation culture of companies comes partially from the internal capabilities [33]. An effective BIM adoption and implementation requires construction stakeholders to consider the organizational structure needed to support BIM [34].

H6. Effectiveness of "industry-based factors" has a direct and positive impact on "BIM effectiveness criteria".

Industrial developments on BIM-related issues are expected to influence the success rate of BIM implementation. A BIM implementation is not likely to be successful at a time when guidelines and BIM protocols are missing [35], commercially available BIM tools are incapable [36], and software platform is not interoperable [37].

H7. Effectiveness of “BIM effectiveness criteria” has a direct and positive impact on “process effectiveness criteria”.

Contribution of BIM implementation to the efficiency of the construction process has been reported in previous studies [38]. Majority of the projects surveyed by Cao et al. [31] revealed the positive influence of BIM implementation on the construction process, where the benefits obtained from improved task effectiveness overwhelmed those related to efficiency improvements.

H8. Effectiveness of “process effectiveness criteria” has a direct and positive impact on “project-related benefits”.

A number of studies have emphasized the favorable project outcomes of BIM implementation obtained by improving the efficiency of the construction process ([34,39]). These studies have reported the positive influences of BIM implementation on the project time, cost, quality, and safety through improving communication, reducing rework, and increasing productivity.

H9. Effectiveness of “process effectiveness criteria” has a direct and positive impact on “company-related benefits”.

An effective construction process is expected to bring not only project level benefits, but also company level benefits that get beyond the limits of the project. The companies that execute the construction process efficiently with the BIM implementation should be more likely to adopt new technologies, improve knowledge management, and increase their reputation.

H_{10}. : Effectiveness of “project-related benefits” has a direct and positive impact on “company-related benefits”.

A construction project that can achieve favorable project outcomes (being completed on time, within budget, and with high quality) can be considered a successful project. Successfully completed projects are believed to result in company-wise benefits in the long run such as improved brand value and long-term profitability.

3.1.2. Deriving the factors

An extensive literature review was conducted to derive the factors of the BIM effectiveness framework. A total of 42 factors were identified at the initial step as a result of reviewing 30 sources. After conducting a pilot study with two university professors and three industry practitioners, the list was refined by either combining or removing some of the factors. The resultant list including 36 factors under 7 constructs is presented in Table 1.

3.1.2.1. Project-based factors. Training the project staff (PBF1): Provision of BIM training programs is an important factor a contractor should consider for successful BIM implementation. It can be provided through a range of instruction strategies such as BIM courses, conferences and forums, training sessions, virtual BIM training programs, blogs, and group study sessions [34]. Majority of organizations send their staff to seminars or training focusing on BIM implementation [58].

BIM knowledge of the project participants (PBF2): Implementation of the BIM in construction projects highly depends on the familiarity of the project participants with the process. The low return on investment experienced by many BIM users around the world can be attributed to lack of BIM knowledge and experience of the users. Thus, smaller companies that do not frequently engage in BIM projects tend to suffer most [13].

Clarification of rights and responsibilities (PBF3): An important issue that must be legally clarified is the rights and responsibilities of project participants. Potential disagreements on copyright issues could be prevented through explaining the ownership rights and responsibilities in the contract documents [40]. Standardized supplementary legal agreements, namely BIM protocols, should be incorporated into the construction contracts.

Table 1
List of factors.

Construct		Factor	Sources
Determinants	Project-based factors	Training the project staff	1, 3, 4, 5, 7, 9, 11, 14, 15, 17, 19, 21, 23, 25, 27, 29, 30
		BIM knowledge of the project participants	1, 7, 11, 12, 13, 15, 19, 24, 27, 30
		Clarification of rights and responsibilities	2, 5, 7, 9, 11, 15, 21, 22, 24, 30
		Commitment to updating the model	2, 9, 11, 13, 17, 20, 25, 30
		Existence of BIM specialists	1, 3, 9, 11, 17, 25, 27, 29, 30
	Company-based factors	BIM experience of the company	3, 9, 11, 13, 19, 20, 23, 24, 25
		Top management support	4, 9, 11, 15, 17, 19, 23, 25, 29
		Hardware and software investments	1, 3, 5, 7, 9, 11, 14, 17, 19, 23, 25, 27
		Employees' computer ability	5, 9, 13, 17, 19, 23, 25, 29
		Existence of company BIM procedures	1, 3, 7, 9, 24
	Industry-based factors	Availability of guidelines/standards	1, 2, 6, 11, 13, 15, 17, 19, 21, 23, 25, 28, 30
		Interoperability of software platform	1, 2, 4, 5, 6, 7, 11, 13, 14, 15, 18, 27, 29, 30
		BIM awareness within industry	5, 6, 7, 15, 17, 19, 21, 23, 25, 27, 29, 30
		Capacity and capability of current software	5, 6, 9, 11, 12, 19
		Availability of BIM protocols	2, 3, 7, 9, 11, 15, 17, 18, 23, 24, 25, 27, 30
Measurement	BIM effectiveness criteria	Proper construction documents	1, 5, 6, 7, 14, 21, 26
		Accurate quantity take-off	2, 3, 4, 6, 7, 8, 9, 16, 22, 23, 26, 28, 30
		Detection/elimination of clashes	2, 3, 4, 5, 7, 8, 9, 13, 15, 16, 20, 21, 22, 23, 24, 26, 30
		Improved cost control mechanism	2, 4, 5, 7, 16
		Better visualization of the project	1, 3, 4, 6, 7, 8, 9, 14, 16, 23, 24, 26, 28, 30
		Scope clarification	5, 14, 28
	Process effectiveness criteria	Improved communications and trust	1, 2, 5, 8, 13, 18, 19, 22, 26, 28, 30
		Reduced lead times and duplications	1, 2, 3, 7, 15, 18, 21, 26, 30
		Better coordination of disciplines	1, 2, 3, 5, 6, 7, 9, 10, 11, 14, 15, 16, 22, 23, 25, 26, 28
		Increased labor productivity	1, 3, 4, 7, 13, 14, 15, 21, 22, 23, 27
		Avoidance of unexpected costs	1, 8, 9, 18, 21
		Reduced change orders/claims/disputes	1, 3, 4, 5, 7, 9, 14, 26
Outcomes	Project-related benefits	Shortened project duration	1, 2, 5, 7, 8, 13, 14, 16, 18, 19, 20, 21, 22, 26, 27, 30
		Reduced project cost	1, 2, 5, 6, 7, 8, 14, 16, 18, 19, 20, 21, 22, 26, 27, 30
		Enhanced product quality	1, 2, 4, 5, 6, 10, 13, 14, 16, 18, 19, 21, 23, 26, 27, 28, 30

(*continued on next page*)

Table 1 (*continued*)

Construct	Factor	Sources
Company-related benefits	Improved health and safety	4, 5, 7, 10, 14, 22, 26, 27, 28
	Client satisfaction	2, 7, 11, 14, 16, 19, 26
	Improved company image/brand value	1, 2, 3, 7, 9, 11, 20
	Enhanced knowledge management	7, 12, 13, 14, 18, 19, 21, 22, 26
	Long-term profitability	1, 2, 3, 14, 20, 23
	Technology adoption	1, 7, 13, 15, 19, 20, 23, 26, 29

1. Ahn et al. [34]; 2. Azhar [40]; 3. Boktor et al. [41]; 4. Cao et al. [31]; 5. Bryde et al. [42]; 6. Bynum et al. [43]; 7. Ghaffarianhoseini et al. [13]; 8. Kim et al. [44]; 9. Hanna et al. [45]; 10. Ding et al. [46]; 11. Won et al. [37]; 12. Korpela et al. [36]; 13. Miettinen and Paavola [47]; 14. Stowe et al. [39]; 15. Porwal and Hewage [35]; 16. Bhirud and Patil [48]; 17. Ahmed [29]; 18. Bhatija et al. [49]; 19. Juan et al. [50]; 20. Cao et al. [51]; 21. Doumbouya et al. [52]; 22. Fadeyi [15]; 23. Harun et al. [53]; 24. Monko et al. [54]; 25. Ozorhon and Karahan [9]; 26. Ghannadpour et al. [55]; 27. Rogers et al. [18]; 28. Shou et al. [56]; 29. Son et al. [8]; 30. Yaakob et al. [57].

Commitment to updating the model (PBF4): Implementing the BIM approach throughout the project requires the company to commit itself truly to the practice and lead to process to take on the challenges. The BIM approach cannot be regarded as a test-drive [45]. The participants should be willing to update the model and utilize it throughout the project phases from the design through construction to the facility management.

Existence of BIM specialists (PBF5): The BIM process should be guided by specialists with great knowledge and experience in BIM implementation to overcome any unexpected situation that might pose an obstacle to the execution of the process. Lack of BIM experts within the company was reported to obstruct implementation of the BIM technology to the construction industry in a couple of studies ([9,29]).

3.1.2.2. Company-based factors. BIM experience of the company (CBF1): Having implemented BIM in numerous construction projects increases the likelihood of companies to achieve success. Even though the technological advantages of BIM have been greatly recognized in the construction industry, it may not be properly implemented by construction companies that do not possess the required technical expertise of or process know-how [51].

Top management support (CBF2): BIM is considered a game-changing technology that influences the work processes, scope/project initiation, resourcing, and tool mapping [59]. Therefore, it requires some organizational changes within the BIM adopting company [50]. The organizational readiness to employ the new technology depends highly on the top management support.

Hardware and software investments (CBF3): Employing the BIM technology requires both hardware and software investments. The former implies the expense of dedicated high-specification workstations. Unlike CAD software packages that can be operated on the majority of professional computers, BIM software necessitates these high-priced workstations. The latter involves BIM software licenses for purchasing, maintaining, and upgrading the software. Compared to the cost of CAD software packages available on the market, BIM software licenses tend to be more expensive [39].

Employees' computer ability (CBF4): Implementation of BIM technology necessitates the project staff to be equipped with computer usage skills. Competency in computer usage helps the employees perform better throughout the BIM process because exploring the advantages of BIM technology requires intense interaction with computer. Moreover, being already exposed to various technologies creates an opportunity to faster adopt a new technology [53].

Existence of company BIM procedures (CBF5): Development of BIM procedures shall promote BIM adoption and implementation on construction projects and within companies. Creation of in-house BIM procedures helps the construction firms better allocate resources and budget [41]. Especially, the companies that consider using the BIM technology in the coming years are suggested to create their internal BIM procedures [45].

3.1.2.3. Industry-based factors. Availability of guidelines/standards (IBF1): A limited number of countries have established their own legal regulations and presented guidelines regarding BIM [60]. Guidelines are nonbinding statements issued by private or governmental organizations to streamline certain processes. BIM guidelines aim to help architects and designers to generate high performance structures. The need to standardize the process was highlighted by Azhar [40].

Interoperability of software platform (IBF2): Interoperability feature of BIM software platforms is among the most fundamental benefits of BIM use. Digitally representing the characteristics of a BIM structure enables the users to transfer both design data and specifications between various BIM software applications [13]. Utilization of software platforms with interoperability problems might hinder data transfer and implementation of the BIM process.

BIM awareness within industry (IBF3): The growing awareness of BIM technology within the construction industry can encourage more construction firms to make use of it and thereby increase the BIM adoption rate. The awareness could be raised through conference and seminars [61]. Another way to build awareness is to select the project leaders among the project managers trained in BIM as they are more likely to implement BIM in the project [52].

Capacity and capability of current software (IBF4): The level of current BIM technology should play an important role in determining the success of BIM-based services. Effectiveness of BIM depends largely on how efficiently available software applications can support the service of interest [37]. The capabilities of BIM software are expected to accelerate in the following years along with the increases in BIM implementation rates.

Availability of BIM protocols (IBF5): A BIM protocol is a contractual guide to the BIM process such as model file formats, model ownership, sharing files, submitting models for review, and responsibility of model changes. It is based on direct contractual relationship between the parties (employer and supplier). It enables the production of BIM models at defined project phases. Use of common standards and protocols is an indicator of value generated by BIM usage [41].

3.1.2.4. BIM effectiveness criteria. Proper construction documents (BEC1): Document errors and omissions have been identified as one of the main sources of waste in the traditional construction workflow [39]. Utilization of BIM software enables decreasing the waste through providing proper construction documents. BIM software tools support producing construction documents without the need for another tool [43].

Accurate quantity take-off (BEC2): BIM has the capacity to provide all the required information throughout the project including spatial relationships, quantity and specifications, list of materials, and cost estimations [62]. Material quantities are automatically given by the model; which improves budgeting, provides cost-loaded schedules, and enables interactive forecasts to make agile comparisons [57]. Quantity take-offs derived from the BIM model are more frequently used in the construction phase rather than the design phase, where utilization of BIM could provide greater benefits for the project cost control [31].

Detection/elimination of clashes (BEC3): Construction models are composed of interdependent and historically changing elements. Changes in one of the elements result in clashes with other elements established in the previous development phase [47]. Utilization of BIM tools can provide great amount of savings in the contract value through detecting these clashes. BIM is used by most of the companies for the purpose of 3D and 4D clash detections [40].

Improved cost control mechanism (BEC4): An effective cost control technique is essential for managing the risk of cost overrun in construction projects. Construction projects involve many stakeholders from various disciplines. The emergence of BIM technology is believed to improve the cost control mechanism by enhancing the collaboration between the stakeholders [63]. BIM ensures better cost control mechanism through making improvements in planning, estimating, budgeting, and controlling the costs [42].

Better visualization of the project (BEC5): An accurate visualization of design is fundamental to figuring out the performance of building. Traditionally, visualization has relied on interpreting orthogonal drawings and envisioning the design based on two dimensional drawings. The advent of BIM enabled tools ensured better visualization of the project by providing high quality renderings, shaded 3D views, and animated walkthroughs.

Scope clarification (BEC6): Clarification of scope is one of the accredited benefits of BIM [64]. BIM allows the architects, engineers, and contractors to work together in a collaborative environment and leads to more efficient design and construction processes. Facilitated and encouraged data sharing among the team members is expected to result in several benefits such as increased reliability, greater transparency, and clarification of scope.

3.1.2.5. Process effectiveness criteria. Improved communications and trust (PEC1): Lack of trust among project stakeholders has been listed among the major factors affecting application of knowledge management in the construction industry [49]. Communication and trust among the project stakeholders have been noticeably improved thanks to the technological advances obtained by the increasing use of BIM. BIM improves communication and trust between the designers and site engineers through supporting a collaborative environment [34].

Reduced lead times and duplications (PEC2): Rework, being one of the chronic problems of the construction industry, has impacts on almost every criterion of the project success. A considerable loss of resources, materials, and workforce-time could be observed as the consequences of rework. A dramatic decrease has been noticed in the emergence of errors and inconsistencies with the widespread use of BIM [62]. Utilization of BIM in the design stage of construction process could result in reducing the lead times and duplications [52].

Better coordination of disciplines (PEC3): In addition to visualization, analysis, and supply chain integration, coordination is among the emerging applications of BIM in the current practices [65]. Complexity of building shapes and systems gives rise to spatial conflicts and clashes, where the advantages of the BIM-assisted space coordination can be realized most [37]. BIM allows project participants from various disciplines to retrieve and generate information from the same model, fostering the collaboration and coordination among them [46].

Increased labor productivity (PEC4): Productivity in construction can be defined as the amount of output generated from certain resources such as materials, equipment, and labor. The need to achieve continuous improvement in the construction productivity points toward the use of BIM [15]. BIM is regarded as the technological innovation required to address falling level of construction productivity [18] and increase the labor productivity in the field by providing precise geometry and data needed to support construction activities [34].

Avoidance of unexpected costs (PEC5): Existence of uncertainty in construction projects brings about many unexpected costs that cannot easily be foreseen at the beginning of the construction process. Utilization of BIM helps avoiding the unexpected costs by decreasing the uncertainty [34] especially in the design phase, where BIM usage could lead to much efficient cost control management process [31].

Reduced change orders/claims/disputes (PEC6): Change orders represent the work added to or deleted from the original scope of work, altering the original contract. Change orders are among the most critical reasons behind the cost growth and disruptions to field productivity [66]. The change orders could be owner-generated or field-generated [67]. Adoption of BIM in construction projects can considerably decrease the number of change orders originating from field conflicts [68].

3.1.2.6. Project-related benefits. Shortened project duration (PRB1): BIM is known to shorten project duration by accelerating the construction period [69]. The additional work of 3D modeling might extend the design phase; however, this extension is expected to disappear in consequence of the increasing familiarity and capability with 3D [18]. Accelerated schedule enables early occupancy of the building and realization of time-to-market opportunities [39].

Reduced project cost (PRB2): BIM has been indicated to provide significant reduction in the total cost of construction projects. Evidence for economic benefits has been a solid reason for adopting the technology [70]. Previously reported analyses have revealed high return on investment results for BIM implementation [13], meaning that notable amount of cost savings could be obtained from BIM investments. Higher cost reduction can be achieved by higher utilization and contribution of BIM [44].

Enhanced product quality (PRB3): BIM utilizes of a set of technologies and organizational solutions to improve quality of design, construction, and maintenance of construction projects [47]. BIM ensures higher production quality by enabling flexible documentation output and automation [48]. Area of utilization of BIM in quality management may involve laser scanning for quality assessment and generation of BIM models from point cloud data for deviation analysis [56].

Improved health and safety (PRB4): Project success has been evaluated in terms of time, cost, and quality. However, safety issues have also drawn great interest in recent years. Economic concerns are no longer the only focus point in project management as safety and security have gained much attention [46]. BIM usage in identifying and preventing safety issues can improve safety and availability of labor [71].

Client satisfaction (PRB5): The accelerating BIM usage leads to increasing profitability, reducing costs, enhancing time management, and improving customer-client relationships [40]. The clients' satisfaction levels are increased through visually verified design intent and knowledge sharing through virtual design and construction [13]. Owners can have greater awareness and more confidence in the design [39].

3.1.2.7. Company-related benefits. Improved company image/brand value (CRB1): Following the latest technological advancements is regarded as one way of demonstrating the competence of the company. BIM is regarded as a ground-breaking development that transforms the building design process. In this respect, construction companies can improve their company images through marketing their BIM capabilities to potential customers [45].

Enhanced knowledge management (CRB2): BIM provides knowledge management benefits to construction firms during both the construction and post-occupancy phases. BIM tools provide capability for integration by allowing inputs from various professionals to be collected under the model [13]. Any input given to the model could be extracted at any time and used both during the current project and for the following projects.

Long-term profitability (CRB3): BIM implementation in construction projects is known to provide economic contribution to the project [43]. However, some implementations fail to be successful due to several reasons such as lack of capable personnel, unfamiliarity with the process, insufficiency of the software, legal issues, etc. In the long run, these problems are expected to disappear thanks to the industrial developments and company investments in BIM. Thus, companies adopting the BIM approach should achieve long-term profitability.

Technology adoption (CRB4): Technology acceptance assessment refers to the intention to accept a new technology. Organizational readiness, on the other hand, indicates the ability of an organization to adopt the new technology [50]. People tend to accept a new technology when they feel ready for the organizational change [72]. BIM implementation in a construction project encourages organizational change within an organization, which would trigger the technology acceptance or adoption.

3.2. Questionnaire survey

A questionnaire survey was designed in accordance with the developed model to quantitatively analyze the interactions between the constructs and determine the factor loadings. The questionnaire was composed of three main sections. The first section involved general questions about the respondent and the company. The second section included project specific questions such as the BIM platforms utilized. The third section was the evaluation of the factors in a 1–5 Likert Scale (very low, low, medium, high, and very high) based on the observations on the BIM implementation in a certain construction project.

The questionnaire was sent online to construction practitioners with BIM experience during the period between December 2019 and January 2020. The targeted respondents were the members of the Turkish Contractors Association and the Chamber of Civil Engineers. Having experienced at least one construction project with BIM implementation was stated as the requirement for participating in the survey. In an effort to increase the response rate, face-to-face interviews were also conducted with well-known and experienced professionals not frequently checking their emails. The interviews included exactly similar questions, but the answers were written down on a piece of paper. Those answers were added manually to the data collected online.

A total of 172 questionnaires were returned out of 653 sent out, resulting in a response rate of 26%. The responses represented 107 different construction projects, where multiple data were obtained from different stakeholders (client, contractor, consultant, designer, subcontractor, etc.) of some projects. The respondents assessed the questions from their point of view and within the scope of their companies.

3.3. Structural equation modeling analysis

The collected 172 questionnaires were used for SEM analysis. SEM is a multivariate analysis technique that allows for modeling complicated relationships between various model components. It can test and assess both the direct and indirect impacts on pre-assumed causal relationships. Implementation of BIM in construction projects, by its nature, incorporates several interactions between the constructs, resulting in a sophisticated system. The BIM effectiveness framework under investigation involved up to ten causal relationships (examined by the hypotheses) between seven different constructs. Therefore, carrying out a SEM analysis was deemed suitable to investigate the nature of BIM effectiveness in the construction industry. SEM models were stated to perform quite well even with 50 to 100 samples. Nonetheless, the simplistic and conservative approach is to collect as much as 200 samples [73]. Xiong et al. [74] reported that out of 84 SEM applications in construction, 26 models had <100 samples, 39 models had 100 to 200 samples, and 19 models had over 200 samples.

3.4. Roadmap development

A roadmap was proposed for the Turkish construction industry to promote the determinants of BIM effectiveness. The roadmap was developed by a team of four academicians and nine professionals (Table 2). Potential actions were provided for project-, company-, and industry-based factors. For each factor, the proposed actions to be taken by various parties were summarized.

Table 2
Profile of the team members.

Team member	Position	Years of experience
A	Professor	30
B	Professor	18
C	Associate Professor	22
D	Associate Professor	11
E	Company Owner	18
F	Digital Transformation Expert in Construction	21
G	Principal Structural Engineer	24
H	Architect	5
I	BIM and Technology Coordinator	7
J	Senior Information Management Lead	8
K	BIM Manager	16
L	BIM Responsible	10
M	Structural/Civil Design Group Lead	14

4. Research results

4.1. Profiles of survey respondents

Respondents had a professional experience of 0–5 years (30%), 6–10 years (35%), 11–15 years (25%), 16–20 years (6%), and 21 years and more (4%). Younger employees have more tendency to participate in such innovative projects as technical innovations require employees to invest in themselves. They need to spend time and effort to get accustomed to the changes the innovation brings about. The professionals are more likely to show internal resistance against innovations if it is uncertain that they can reap the benefits of these investments [75]. The greater part of the respondents were engineers/architects (53%) followed by department chiefs/managers (21%), coordinators/directors (12%), technicians (10%), and owners/board members (4%).

Respondents provided information about the companies that they worked for during the BIM project for which they evaluated the SEM questions. The companies where the respondents worked were dominantly designers (37%) and contractors (32%); which could be regarded as the main contributors of the BIM approach. The remaining one third of the companies were composed of subcontractors (11%), consultants (10%), and clients (10%). The respondents also indicated the type of client in the project. The client types were dominated by private sector clients (62%), while public sector clients corresponded to 38% of the projects. Most of the samples were collected from the building projects (64%) followed by the infrastructure projects (16%), industrial projects (8%), and highway projects (6%), airports (4%), museums (1%), and water structures (1%).

BIM applications are presented in Fig. 3. Evaluation of design alternatives and constructability analysis, which are two crucial activities that take place in pre-design stage, were noticed to be the most frequently practiced BIM implementation fields with percentages of 83% and 69%, respectively. Pre-design is the key construction stage to create value addition to the project ([76,77]) and these activities can play critical role in increasing the project value.

The respondents stated which BIM platforms they had utilized in their projects (Fig. 4). It is realized that Autodesk Revit was dominantly the most preferred BIM platform, which was utilized in almost all the projects (95%). Another noteworthy BIM platform that took place in more than one fourth of the projects is Tekla Structures (27%). The other BIM platforms were utilized in <10% of the projects.

4.2. Model results

The developed hypotheses were tested with the SEM approach. The initially developed model comprised a total of ten hypotheses. An insignificant path was identified between the industry-based factors and BIM effectiveness criteria. In an attempt to improve the fit indices, the

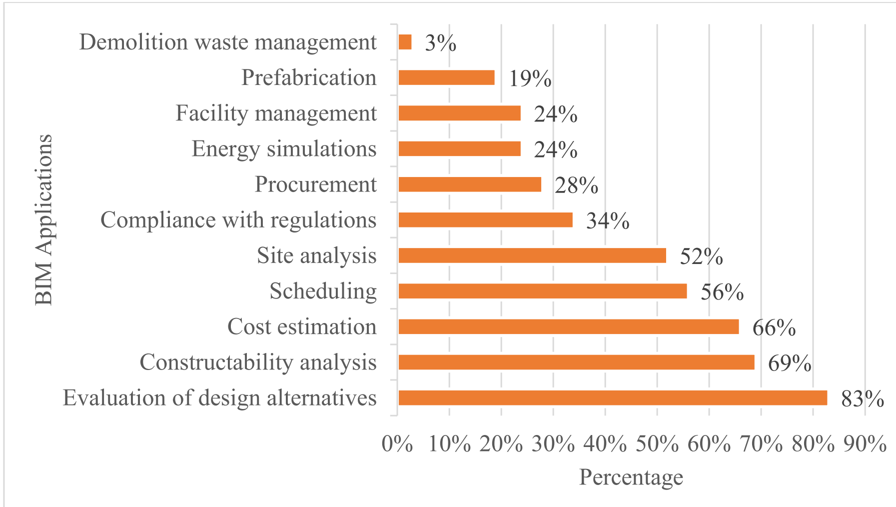

Fig. 3. BIM applications.

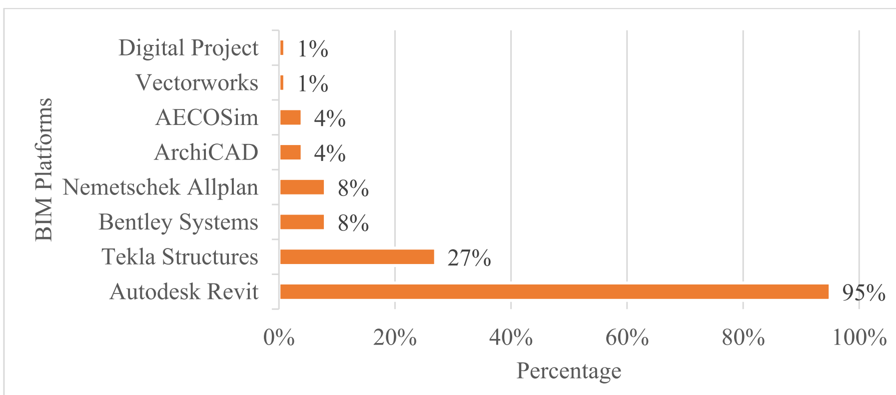

Fig. 4. BIM platforms utilized in the projects.

model was modified. The insignificant hypothesis (H_6) was removed from the initial model and the modified model was re-analyzed.

The path coefficients of the modified model are demonstrated in Fig. 5. The arrows show the direction of influence among the model constructs and the grades (path coefficients) indicate the level of influence. The path coefficients can also be regarded as the regression weights with no intercept term. The level of associations among the constructs was assessed based on a guideline recommended by Murari [78]. According to the guideline, path coefficients between 0.1 and 0.3 stand for week association, path coefficients between 0.3 and 0.5 imply moderate association, and a strong association is indicated by path coefficients over 0.5. The modified model included 6 strong (dark arrows) and 3 moderate (light arrows) associations among the latent variables.

A typical SEM model should satisfy the content and construct

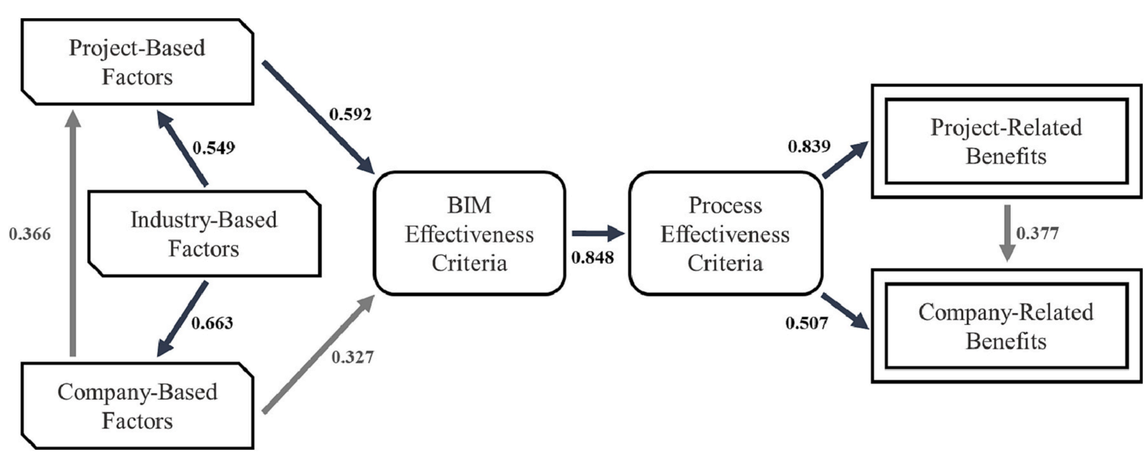

Fig. 5. Path coefficients of the modified model.

validities. No statistical analysis exists to test the content validity. The researcher's judgement was mainly applied for model generation. The constructs and their interactions were finalized according to the suggestions of an expert group composed of two practitioners and two academicians. The indicators of each construct were determined as a consequence of an in-depth literature review.

Construct validity is satisfied through scale reliability, discriminant validity, and convergent validity. Scale reliability is tested by internal and composite reliability (Table 3). The former was measured by Cronbach's alpha coefficients, which were >0.70 as suggested by Nunally [79]. The latter was also satisfied as the coefficients were >0.6 [80].

Convergent validity was checked to determine if all observed variables forming a latent variable converge to a single latent variable. It was assessed through the average variance extracted (AVE) scores presented in Table 3. The scores ranged between 0.45 and 0.66. AVE values are suggested to be >0.5 for convergent validity. However, convergent validity still holds if the AVE scores of some latent variables are lower than 0.5, but composite reliability is >0.6 [81].

Discriminant validity was tested to make sure that constructs did not measure the same phenomenon. The correlation between any two constructs should be smaller than the square root of AVE for each construct. The test of discriminant validity is presented in Table 4. The requirement was achieved for all the constructs.

The goodness-of-fit is checked through χ^2/dof, comparative fit index (CFI), Tucker Lewis index (TLI), and the root mean square error of approximation (RMSEA). The reliability and fit indices of the model are presented in Table 5. The values were noticed to satisfy the limits recommended by Kline [82]. Noticeable improvements were observed in fit indices after modification.

Factor loadings of the observed variables are summarized in Table 6. A factor loading represents the correlation between an observed variable and the corresponding construct. A higher factor loading implies a higher correlation. The observed variables with the highest and lowest factor loadings are interpreted for each construct in the discussion section.

A roadmap for BIM implementation is presented in Table 7. Certain actions were proposed to enhance the performance of project-, company-, and industry-based factors. The party/parties that can put the action into practice were indicated at the end of each action. The party/parties could either be the construction companies, government bodies, or non-profit organizations.

5. Discussion

5.1. Interactions between the constructs

The results of the SEM analysis for the proposed BIM effectiveness framework demonstrated that in addition to the causal links between the determinants, measurements, and the outcomes; interactions exist between the determinants (project-, company-, and industry-based factors). Certain constructs (especially the industry-based factors) mainly affect the other determinants rather than exerting a direct influence on the BIM effectiveness. This situation pointed out the importance of investigating the indirect effects.

Path coefficients of the modified model showed that project-based factors had the greatest influence on the effectiveness of BIM implementation followed by the company-based factors. This means that a

Table 3
Test of reliability and convergent validity.

Latent variables	Cronbachs's Alpha	Composite reliability	AVE
Project-based factors	0.884	0.856	61.89%
Company-based factors	0.886	0.881	63.05%
Industry-based factors	0.837	0.818	51.60%
BIM effectiveness criteria	0.830	0.841	45.41%
Process effectiveness criteria	0.903	0.910	60.56%
Project-related benefits	0.829	0.808	47.44%
Company-related benefits	0.884	0.916	66.28%

Table 4
Test of discriminant validity.

Construct	PBF	CBF	IBF	BEC	PEC	PRB	CRB
PBF	**0.787**						
CBF	0.585	**0.794**					
IBF	0.624	0.528	**0.718**				
BEC	0.634	0.613	0.570	**0.674**			
PEC	0.577	0.468	0.551	0.640	**0.778**		
PRB	0.530	0.432	0.439	0.596	0.658	**0.689**	
CRB	0.546	0.522	0.470	0.602	0.636	0.642	**0.814**

Table 5
Reliability values and fit indices of the model.

Index	Recommended value	Initial	Modified
Cronbach's alpha	> 0.70	0.961	0.961
χ^2/dof	< 3.00	1.997	1.847
CFI	0 (no fit) to 1 (perfect fit)	0.858	0.880
TLI	0 (no fit) to 1 (perfect fit)	0.847	0.870
RMSEA	< 0.10	0.076	0.070

Table 6
Factor loadings of the observed variables.

Construct	No	Variable name	Value
Project-Based Factors	PBF1	Training the project staff	0.651
	PBF2	BIM knowledge of the project participants	0.756
	PBF3	Clarification of rights and responsibilities	0.795
	PBF4	Commitment to updating the model	0.826
	PBF5	Existence of BIM specialists	0.879
Company-Based Factors	CBF1	BIM experience of the company	0.740
	CBF2	Top management support	0.802
	CBF3	Hardware and software investments	0.848
	CBF4	Employees' computer ability	0.763
	CBF5	Existence of company BIM procedures	0.813
Industry-Based Factors	IBF1	Availability of guidelines/standards	0.714
	IBF2	Interoperability of software platform	0.797
	IBF3	BIM awareness within industry	0.611
	IBF4	Capacity and capability of current software	0.755
	IBF5	Availability of BIM protocols	0.702
BIM Effectiveness Criteria	BEC1	Proper construction documents	0.741
	BEC2	Accurate quantity take-off	0.658
	BEC3	Detection/elimination of clashes	0.675
	BEC4	Improved cost control mechanism	0.581
	BEC5	Better visualization of the project	0.571
	BEC6	Scope clarification	0.762
Process Effectiveness Criteria	PEC1	Improved communications and trust	0.752
	PEC2	Reduced lead times and duplications	0.780
	PEC3	Better coordination of disciplines	0.740
	PEC4	Increased labor productivity	0.793
	PEC5	Avoidance of unexpected costs	0.756
	PEC6	Reduced change orders/claims/disputes	0.812
Project-Related Benefits	PRB1	Shortened project duration	0.574
	PRB2	Reduced project cost	0.646
	PRB3	Enhanced product quality	0.800
	PRB4	Improved health and safety	0.573
	PRB5	Client satisfaction	0.811
Company-Related Benefits	CRB1	Improved company image/brand value	0.746
	CRB2	Enhanced knowledge management	0.885
	CRB3	Long-term profitability	0.812
	CRB4	Technology adoption	0.809

Table 7
Roadmap for BIM implementation.

Project-Based Factors	Company-Based Factors	Industry-Based Factors
(PBF1) Training the project staff: - Prepare quick cards and informative material* - Provide in-house training* - Organize BIM conferences and seminars*, **, *** - Plan BIM training programs*, **, ***	(CBF1) BIM experience of the company: - Use BIM in projects even if it is not mandatory* - Familiarize experienced staff with BIM process* - Execute pilot BIM projects*, ** - Mandate BIM use**, ***	(IBF1) Availability of guidelines/standards: - Use international BIM guidelines/standards* - Develop BIM guidelines/standards**, *** - Establish BIM programs and committees**, ***
(PBF2) BIM knowledge of the project participants: - Subcontract with BIM experienced firms* - Adapt business process to BIM implementation* - Quantify BIM influence on company success* - State commitment to BIM adoption*, **	(CBF2) Top management support: - Bid for projects with BIM requirement* - State commitment to BIM adoption*, ** - Set reward mechanisms for BIM excellence** - Mandate BIM use**, ***	(IBF2) Interoperability of software platform: - Prefer BIM platforms with IFC support* - Provide feedback to the BIM platform supplier* - Prefer software from the same software company* - Organize seminars on open-standard data formats*, **, ***
(PBF3) Clarification of rights and responsibilities: - Use BIM protocols developed by the pioneers* - Place clear contract clauses* - Develop BIM protocols**, *** - Establish BIM programs and committees**, ***	(CBF3) Hardware and software investments: - Periodically renew workstations* - Buy software programs as a package* - Quantify BIM influence on company success* - Set reward mechanisms for BIM excellence**	(IBF3) BIM awareness within industry: - State commitment to BIM adoption*, ** - Set reward mechanisms for BIM excellence** - Establish BIM programs and committees**, *** - Organize BIM conferences and seminars*, **, ***
(PBF4) Commitment to updating the model: - Report updated model periodically* - Adapt business process to BIM implementation* - State commitment to BIM adoption*, ** - Set reward mechanisms for BIM excellence**	(CBF4) Employees' computer ability: - Provide in-house training* - Assign personnel with high computer skills* - Plan training programs for computer usage**, ***	(IBF4) Capacity and capability of current software: - Use BIM software with high-end capabilities* - Inform the supplier about the incapabilities* - Organize workshops on software capabilities*, **, ***
(PBF5) Existence of BIM specialists: - Recruit BIM experienced personnel* - Incorporate key personnel into BIM process* - Plan BIM training programs**, *** - Organize BIM conferences and seminars*, **, ***	(CBF5) Existence of company BIM procedures: - Align an existing BEP with the firm's vision* - Develop BEP*, **, *** - Establish BIM programs and committees**, ***	(IBF5) Availability of BIM protocols: - Use BIM protocols developed by the pioneers* - Place clear contract clauses* - Establish BIM programs and committees**, *** - Develop BIM protocols**, ***

* Construction Companies.
** Government Bodies.
*** Non-Profit Organizations.

corporate company with a solid BIM infrastructure (highly skilled employees, supporting top management, adequate hardware and software investments, etc.) may not implement BIM effectively unless the company reflects its capabilities on the project conditions. Impact of project characteristics on the BIM success has also been emphasized in a study investigating BIM implementation in Chinese construction industry [31].

Company-based factors both directly and indirectly affected the BIM effectiveness. The direct effect was noticed to be at moderate level. Certain company characteristics can play an important role in achieving the BIM implementation success. To illustrate, Ghaffarianhoseini et al. [13] stated that the degree of BIM comprehension and adoption could be related to the size of an AEC firm. In addition to the direct effect, company-based factors can indirectly affect the BIM implementation through influencing the project-based factors. A moderate level of association was observed among the company-based factors and project-based factors, which is an indication of favorable project environments enabled by capable companies.

The path between the industry-based factors and BIM effectiveness was found insignificant. It means that maturity of the BIM technology in the construction industry does not directly result in an effective BIM implementation. Backing up this finding, the study conducted by Chen et al. [22] revealed no significant impact of any environmental factor. Nonetheless, it should be noted that industry-based factors can indirectly promote BIM success through contributing to project- and company-based factors. Industry-based factors were detected to be strongly associated with both the project- and company-based factors. It is reasonable to infer that maturity of the BIM technology can be regarded as an incentive for the construction companies to (i) adapt themselves to the technology and (ii) build favorable project environment. Construction companies are disposed to making necessary infrastructural and software investments when the incentive is there [13].

The interactions between the determinants and BIM effectiveness were illustrated in Fig. 6 based on the results. The area of influence was observed to increase by moving outward, demonstrating the influence of the industry-based factors on the others. The darkness of the shaded areas represented the intensity of the influence on BIM effectiveness. It was noticed to increase by moving inward, explaining the strong influence of the project-based factors and the insignificant direct influence of the industry-based factors.

The results revealed a strong association between the BIM effectiveness and the effectiveness of the construction process. According to the results, a successfully built BIM model could give rise to a smooth construction process with coordinated project teams, less rework, and high labor productivity. Contribution of the BIM effectiveness to the construction process effectiveness has been highlighted in many studies investigating the effects of BIM implementation in construction projects ([15,34,35,40]). The results for the Turkish construction industry confirmed its contribution by demonstrating the strong association between them.

The effectiveness of the construction process was observed to directly influence both the project- and company-related benefits. The levels of associations were found strong for both paths, where process effectiveness was noticed to have slightly greater impact on the former. It might be explained by the fact that project outcomes indicate the short-term consequences that are realized at the end of the project, while the benefits at the company level are determined by all the projects carried out by the company (Fig. 7). More precisely, a successfully executed construction process is expected to bring about desired outcomes in terms of time, cost, and quality for the corresponding project as they are directly associated. Nonetheless, the company characteristics are shaped not only by a single project but also by the other projects executed by the company. A successfully executed construction process of a single project, thus, can provide limited benefits at the company-level. The process effectiveness could also indirectly provide company-related benefits through promoting the project-related benefits. A moderate level of association was detected between the project- and company-related benefits.

5.2. Evaluation of the observed variables

Factor loadings of the observed variables revealed the most significant project-based factors as existence of BIM specialists (PBF5) and commitment to updating the model (PBF4). BIM concept is relatively new to Turkish construction industry. Its implementation has gained acceleration, especially in the last five years. The respondents

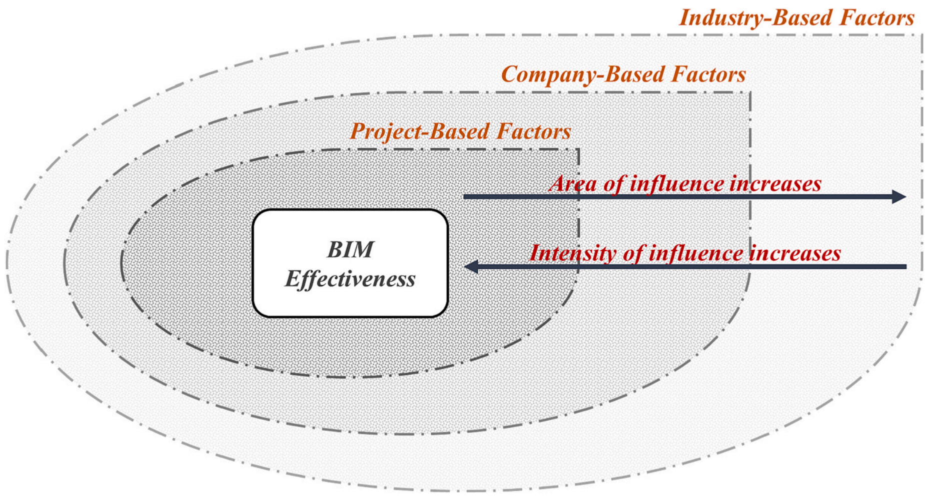

Fig. 6. Influences of the BIM effectiveness determinants.

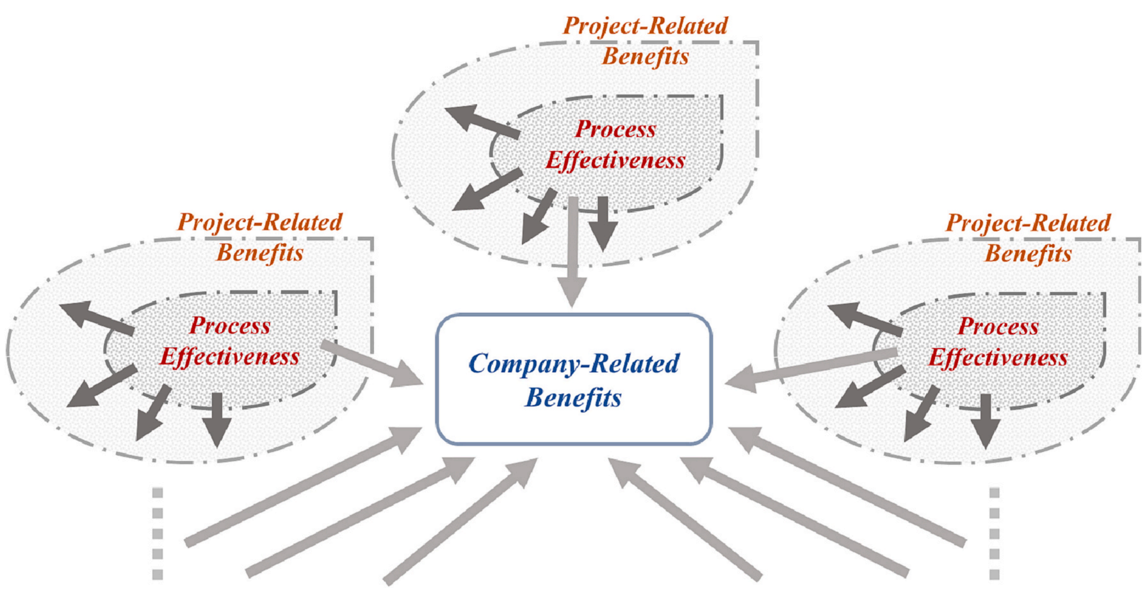

Fig. 7. Impacts of the process effectiveness.

appreciated the ability of BIM specialists to increase the chance of successful BIM implementation through guiding their unexperienced companies and leading the team members. In order to implement BIM effectively, emphasis should also be given to updating the model. In many cases, Turkish construction companies start the project with a great motivation to flawlessly implement BIM. However, they lose their motivation and stop updating the BIM model as they encounter some challenges. In that sense, it is of prime importance for Turkish construction companies to be committed to the BIM process and updating the model. Backing up this finding, the willingness to adopt BIM was observed to be more significant than other technical and nontechnical factors in another study [37].

Hardware and software investments (CBF3) and existence of company BIM procedures (CBF5) were the most crucial company-based factors. Even though BIM technology contains financial risks associated with capital investments in hardware (dedicated high-specification workstations) and software (BIM software licenses), this study demonstrated the profitability of these investments. Turkish construction companies mostly refuse to modernize their technological infrastructures due to the additional costs it would bring. They consider it an unnecessary investment as the existing infrastructure can already support the traditional project delivery methods. Lack of modernization unfortunately prevents the companies from effectively implementing the BIM concept. To support this finding, Khosrowshahi and Arayici [83] also concluded in their studies that the capital required to invest in hardware and software could be the least significant barrier. Company BIM procedures were also stated to be essential for effective BIM implementation. Currently, majority of Turkish construction companies do not have sufficient know-how for BIM implementation. Hence, guidance becomes more of an issue for them to promote success in BIM projects. Such a guidance can be provided by the creation of in-house BIM procedures. In a recent study, investing in the creation of in-house BIM procedures was determined as the investment planned by majority of the respondents in the following years [45]. Companies willing to develop their own BIM procedures can look over the requirements of a widely accepted BIM execution plan (BEP) and complete the sections in line with their project/company characteristics. They can also obtain information from previously conducted studies focusing directly on the development/adoption of BEP ([84,85]).

The most significant industry-based factors were interoperability of software platform (IBF2) and capacity and capability of current software (IBF4). Utilization of various BIM functionalities requires the designers to make use of a number of BIM software. How well the data is exchanged among them (by using open-standard Industry Foundation Classes) implies how efficiently the functionalities are utilized. Interoperability has frequently been perceived as a critical factor for successful BIM adoption ([86,87]). Fortunately, Turkish construction companies have accelerated BIM implementation rate in their projects in the last five years, when the interoperability issues were resolved to a certain extent. Capability of software is of vital importance for reflecting the BIM theories on the project. If the software is incapable of performing the BIM functionalities smoothly, the objectives simply cannot be carried into execution. Software capability should not only be crucial for the Turkish construction industry, but also for global BIM implementation. The capability of a software to support services of interest was also emphasized in another study [37].

The most significant BIM effectiveness criteria were scope clarification (BEC6) and proper construction documents (BEC1). Turkish construction projects that involve many companies with different areas of expertise are frequently subjected to changes and it quite often becomes challenging to determine the scope of each company. At this point, BIM implementation can facilitate the clarification of scope as it provides clear 3D model of the project in early design phase. Clarification of scope enables project managers to make better resource allocation and cost control. It should be noted that scope clarification can be achieved not only by BIM based tools, but also by traditional 3D modeling tools [42]. Interestingly, a previously conducted study reported a limited effect of BIM on the predictability of the project scope [23]. Another challenge in the Turkish construction industry was observed as the document errors and omissions. These errors and omissions can result in costly mistakes on site. As the rapidly changing nature of construction projects throughout the construction phases requires the construction documents to be revised frequently, such mistakes can pose considerable financial risks. BIM adoption was stated to enhance documentation quality by providing a flexible and automated documentation process [40].

The most significant process effectiveness criteria were reduced change orders/claims/disputes (PEC6) and increased labor productivity (PEC4). Innumerous conflicts take place in Turkish construction industry resulting in many claims and disputes. These conflicts are radically decreased with the help of BIM software that enable early detection and solution of the conflicts, which in turn results in significant amount of time and cost savings for the Turkish construction companies. Notable reduction in the number of change orders was also reported in another study investigating the benefits of BIM implementation [64]. Reduction in the number of change orders also gives rise to increased productivity. Low productivity usually stems from the discontinuity of work resulted by conflicts/change orders. Loss of productivity has been demonstrated to be directly associated with the change orders [88]. BIM implementation can increase productivity by providing continuity of work on site and making the workers understand the project and their scope in detail. Olawumi and Chan [16] reported improved productivity and efficiency as the most significant BIM implementation benefit among 36 factors.

The most significant project-related benefits were client satisfaction (PRB5) and enhanced product quality (PRB3). As already mentioned, clients are the promoters of BIM implementation in Turkish construction projects. In most instances, BIM implementation in the project is requested (made obligatory to take part in the tendering phase) by them. Especially, the public clients place emphasis on BIM implementation to build up reputation. BIM implementation enables the contractor to better communicate changes with the client [42], resulting in higher client satisfaction. The positive influence of BIM on both the design and construction qualities has been a widely acknowledged phenomenon [89]. Quality enhancements are noticed due to the early identification and resolution of conflicts before they are reflected on site. Reducing the number of conflicts improves the quality of the product. The ability of BIM integration to enhance the overall project quality has also been reported by Olawumi and Chan [16] among the most significant benefits.

The most significant company-related benefits were enhanced knowledge management (CRB2) and long-term profitability (CRB3). Turkish construction companies don't seem to systematically keep the old project documents and effectively manage the data. In this respect, BIM implementation helps them create systematic construction documents and extract data whenever necessary. Data obtained from previous projects can also be used for the analysis/comparison of subsequent projects and increase the chance of obtaining desirable outcomes. The profitability of construction companies varies greatly depending on the type of project and some project specific conditions. BIM implementation provides better understanding/analysis of the project and decreases the possibility of encountering unexpected situations, thereby mitigating the fluctuations in the project profits. Turkish construction companies frequently get involved in various types of projects taking place at different regions with distinctive characteristics. The unique nature of construction projects (size, type, location, complexity, sociocultural and political environment, etc.) causes the construction companies to operate under a risky atmosphere. Turkish construction companies adopting the BIM approach can mitigate the risks by unveiling the unexpected situations in the design phase and monitoring them during construction [27] and thus, can sustain long-term profitability.

5.3. BIM implementation roadmap

As explained in the above sections, a roadmap was proposed to promote BIM in the construction sector and within this context, several project-, firm-, and industry-oriented strategies were developed to enhance effectiveness of the BIM implementation model variables. The objective was to address all BIM determinants as presented in the initial research framework. Several tools, policies, and strategies had been recommended as part of previous studies in the literature and this study benefited from all to develop its hypothesis and to shape its roadmap as well.

The efforts of the public and private sectors for BIM adoption have been investigated by several researchers [90]. The researchers have listed actions taken by various organizations in leading countries (United States, Sweden, China, Korea, United Kingdom, Netherlands, Singapore, Norway, Denmark, Japan, Hong Kong, Australia, Taiwan, etc.) to diffuse BIM countrywide. This study goes beyond previous work by distinguishing the levels of determinants and stakeholders involved in the process.

The proposed roadmap offers a refined list of activities to be undertaken by various stakeholders and by this way contributed to both literature and practice. The recommendations are in line with the findings reported in earlier studies but more importantly reflect the perception/opinions of key individuals who have relevant experience in the field. The outcome of these strategies can be observed over the years and validated by the professional practitioners.

6. Conclusion

This study proposed a BIM effectiveness framework for construction companies. The framework was composed of the determinants (project-, company-, and industry-based factors), the measurements (BIM effectiveness and process effectiveness criteria), and the outcomes (project- and company-related benefits). A total of 172 samples obtained from 107 different construction projects were analyzed to test the developed hypothesis and validate the framework by using SEM.

Major observations of the study are:

- Effectiveness of BIM implementation in construction projects is determined mostly by the project-based factors followed by the company-based factors.

- Industry-based factors do not have any direct impact on the effectiveness of BIM implementation, but they indirectly affect it through exerting influences on the project- and company-based factors.
- A strong association exists between the effectiveness of BIM implementation and the effectiveness of the construction process.
- Effectiveness of the construction process directly influences both the project- and company-related benefits, where slightly greater impacts are observed on the project-related benefits.

A number of recommendations are provided to construction companies based on the observations as follows:

- Project conditions should be favorable for effective BIM implementation. Availability of BIM specialists is of prime importance to lead the BIM process and guide the team members. Companies should either recruit BIM experienced personnel specifically for the project or assign their key personnel to the project. The project team should be committed to updating the model. Even though generating the BIM model and updating it periodically can be demanding in terms of time and effort, the project team should be aware of the potential benefits and devote themselves to enhancing the accuracy of the model.
- The corporate culture should assist BIM implementation. Construction companies should take all the necessary steps to promote BIM effectiveness. They should not hesitate to invest in necessary hardware and software. They usually refrain from any attempt that may increase the costs. However, they should regard BIM implementation as an investment where the savings exceedingly outweigh the costs. Construction companies should also create in-house BIM procedures. Each construction company has its own organizational structure, participates in certain project types, and has different expectations from the BIM software. Therefore, in-house BIM procedures should be developed such that they perfectly fit the company's needs. A company can align an existing BEP with its vision.
- The maturity of BIM technology in the construction industry should be taken into account. Companies should accelerate BIM investments (both company-wise and project-wise) in line with the technological advances in BIM. In this respect, attention should be given to the interoperability of the software platform and capabilities of commercially available software. The software platform should be fully interoperable, implying that no information loss should occur while exchanging data between various software. The commercially available software should be capable enough to enable utilization of BIM functionalities smoothly. Implementation of the BIM concept in a construction project makes sense only if the software can deliver what the construction company intends to receive.

The main limitation of the study is that since the data was obtained from the BIM practitioners of Turkish construction companies, the results (model validity and reliability, factor loadings, and path coefficients) reflect their perceptions and experiences. Nevertheless, considering the appraised experience of the Turkish professionals especially in the international projects, the results and corresponding strategies can be generalized. Another limitation is regarding the development of hypotheses among the constructs and identification of the underlying factors. The hypotheses were developed and underlying factors were identified based on the literature review and expert suggestions, which might be subjected to personal judgement to a certain extent. It should also be noted that investigating the proposed framework requires technical/computing support. Thus, the extent of analyses and discussion depends highly on the limits of the adopted SEM approach and capabilities of the commercially available software.

The proposed framework contributes to the body of knowledge by (i) determining the constructs of BIM implementation, (ii) specifying the interactions among them, (iii) identifying and prioritizing the underlying factors, and (iv) presenting a roadmap. Construction companies are suggested to make use of the proposed framework and recommendations provided to improve the effectiveness of BIM implementation in their projects. They can utilize the framework to learn the factors and their influences on BIM effectiveness, perceive how BIM effectiveness promotes construction process effectiveness, and realize the project- and company-wise benefits. Government officials are expected to pay attention to the roadmap and accelerate BIM diffusion across the country. Actions specified in the roadmap can be executed by the corresponding parties and improvements in the project-, company-, and industry-based factors can be observed.

The study adopts a systematic approach to investigate the effectiveness of BIM implementation through proposing a novel conceptual framework. Future researchers may benefit from the study by using the proposed framework to conduct similar studies in other countries so that the results can be compared to observe potential differences in BIM implementation across the world. Combination of the results of multiple studies addressing the same question might provide an opportunity to conduct a meta-analysis, which leads to a better understanding of the BIM effectiveness phenomenon.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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