Advances in Civil Engineering

Advanced BIM Applications in the Construction Industry

Lead Guest Editor: Tatjana Vilutiene
Guest Editors: Mohammad R. Hosseini, Eugenio Pellicer, and Edmundas K. Zavadskas

Advanced BIM Applications in the Construction Industry

Advanced BIM Applications in the Construction Industry

Lead Guest Editor: Tatjana Vilutiene
Guest Editors: Mohammad R. Hosseini, Eugenio Pellicer, and Edmundas K. Zavadskas

Editorial Board

Contents

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 6356107, 3 pages
https://doi.org/10.1155/2019/6356107

Editorial

Advanced BIM Applications in the Construction Industry

Tatjana Vilutiene,[1] **M. Reza Hosseini**,[2] **Eugenio Pellicer**,[3] **and Edmundas K. Zavadskas**[4]

[1]*Department of Construction Management and Real Estate, Faculty of Civil Engineering, Vilnius Gediminas Technical University, Vilnius 10223, Lithuania*
[2]*School of Architecture and Built Environment, Deakin University, Geelong 3220, Australia*
[3]*School of Civil Engineering, Universitat Politecnica de Valencia, 46022 Valencia, Spain*
[4]*Institute of Sustainable Construction, Faculty of Civil Engineering, Vilnius Gediminas Technical University, Vilnius 10223, Lithuania*

Correspondence should be addressed to Tatjana Vilutiene; tatjana.vilutiene@vgtu.lt

Received 7 July 2019; Accepted 7 July 2019; Published 25 August 2019

1. Introduction

Rapid technological advancements along with the fierce competition in the construction market for providing better services have stimulated profound change towards using innovative methodologies in the construction industry. With this in mind, there is consensus among researchers and practitioners that construction organizations must draw upon the constant industrial digitalization trend as an opportunity to modify current practices and apply new ways of delivering construction projects. Of these, Building Information Modeling (BIM) is currently considered the most innovative methodology across the construction sector. In its core, BIM provides an intelligent digital representation of buildings to support diverse activities throughout the lifecycle of projects, bringing about a wide range of benefits for various aspects of the delivery process.

Despite the major technical advancements associated with BIM, its adoption across the industry is still low, largely due to the necessity of substantial change across the 25 supply chains, as well as risks and challenges associated with this change. This special issue aims to set a stage for researchers in presenting their findings on current BIM practices, advanced developments, and critical analysis of BIM pillars in applying BIM-enabled practices: technology, people, and processes.

2. Contributions

The special issue includes 16 research articles and 2 review studies. The papers contribute to raise awareness of the advanced developments in BIM practices by offering a critical analysis of various methodologies and tools as well as sociotechnical features of BIM to be considered in applying it in construction projects.

In terms of geographic contexts of the submissions, the special issue brought together researchers from various areas of the world, while a majority of submissions came from Asia (Figure 1 and Table 1).

Building information modeling (BIM) is a set of technologies that aim to increase interorganizational and cross-disciplinary collaboration in the architecture, engineering, and construction (AEC) industries to promote productivity and the quality of design, construction, and maintenance stages of a building. Studies on BIM adoption in small and medium-sized enterprises (SMEs) have remained an underrepresented area. P. Li et al. in their paper titled "Critical Challenges for BIM Adoption in Small and Medium-Sized Enterprises: Evidence from China" propose five strategies for BIM adoption in SMEs. The strategies may help practitioners gain an in-depth understanding of BIM adoption in SMEs from a stakeholder-oriented perspective. Structural engineering companies (SECs) are currently affected by various deficiencies that hinder their processes and

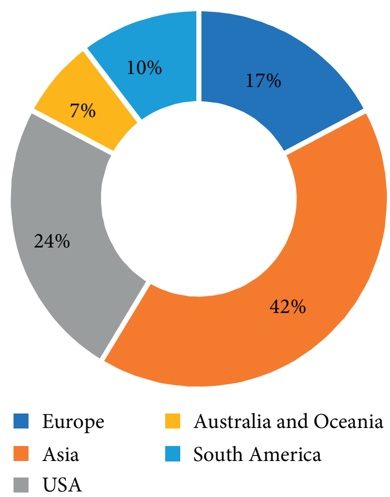


Figure 1: Number of publications from different continents.

Table 1: Contributions by countries.

Countries	Number of contributions
Republic of Korea	5
USA	5
China	4
Chile	2
Spain	2
Australia	2
Taiwan	2
Colombia	1
Poland	1
Hong Kong	1
Lithuania	1
Portugal	1

interactions, productivity, and collaborative and interconnected processes. The paper titled "Methodology for Building Information Modeling (BIM) Implementation in Structural Engineering Companies (SECs)" by F. M.-La Rivera et al. proposes a methodology to implement BIM in the SECs, focused on solving the complexities of the design phase. The methodology clearly and objectively identifies the resources and expectations of organizations, sets out the requirements necessary to BIM adoption, and provides practical and technical recommendations for planning and monitoring its implementation.

The BIM use assessment (BUA) tool presented by M. J. Rojas et al. in the paper titled "BIM Use Assessment (BUA) Tool for Characterizing the Application Levels of BIM Uses for the Planning and Design of Construction Projects," contributes to the diagnosis of the application of BIM uses, thereby enabling companies and clients to identify the BIM use state of the project, the way in which the BIM uses are being implemented, and opportunities for improvement. The proposed tool can be used to evaluate companies to be contracted seeking for the specific BIM use level or also for benchmarking the BIM use level in the industry. The review on building information modeling based on construction networks (BbCNs) conducted by B. Guo and T. Feng provides a valuable reference to the developers of BbCNs to understand the major barriers in their decision-making and to the government aiming at promoting BIM or BbCNs in the construction industry with relevant policies and incentives.

In a building context, decisions made early in the design phase can have a major impact on maintainability of the resulting facility. The paper titled "Augmented Reality for Identifying Maintainability Concerns during Design" by I. A. Khalek et al. examines the extent to which different visualization media may be able to enable individuals without prior maintenance experience to identify maintainability concerns in a design model. Results indicate that BIM supports better identification of potentially problematic areas, but augmented reality (AR) allows users to more consistently determine why an area is problematic; this way, there is an opportunity to use a hybrid approach for identifying and resolving maintainability considerations during the design phase. S. Alsafouri and S. K. Ayer in their article titled "Leveraging Mobile Augmented Reality Devices for Enabling Specific Human Behaviors in Design and Constructability Review" present how augmented reality can support effective design and constructability and demonstrate how the context, in which different types of mobile computing devices are applied, impacts the ways in which they are used. This may help future practitioners and researchers to strategically choose to use, or not to use, certain types of devices to elicit specific behaviors.

The papers by J.-S. Lee et al. and N. Ham and S. Lee investigate the advantages of digital fabrication. The study conducted by J.-S. Lee et al. presented in the paper titled "BIM-Based Digital Fabrication Process for a Free-Form Building Project in South Korea" proposes a BIM-based digital fabrication process for prefabricated parts of buildings. The proposed process is a generalized model that can be universally applied even though the characteristics of digital fabrication might change owing to numerous variables, such as the target project, part, type, form, scale, and material. The BIM-based digital fabrication methodology enables communication, collaboration, and coordination with construction companies, construction project managers, and professional construction companies and provides error minimization and time reduction.

The BIM methodology integrated with available technologies helps to solve different problems that arise during construction in a more efficient way. The study conducted by Y. Ji et al. titled "A BIM-Based Study on the Comprehensive Benefit Analysis for Prefabricated Building Projects in China" analyses the implementation of BIM to identify the economic impact of different construction techniques, in this case, the prefabricated construction techniques. Construction progress is simulated when the case study is rationally transformed from the prefabricated to the conventional in situ construction technique. The study conducted by N. Khan et al., "Excavation Safety Modeling Approach Using BIM and VPL," proposes an automatic safety rule compliance approach for excavation works leveraging algorithmic modeling tools and BIM technologies.

C. Kim et al. in "Automated Conversion of Building Information Modeling (BIM) Geometry Data for Window Thermal Performance Simulation," introduce a BIM data conversion program and illustrate a practical problem of energy performance simulation for a window set. This procedure may lead to the increased use of certification through simulation.

The adoption of BIM integrated with web technology for construction projects allows users to manage interfaces and obtain responses effectively. Y.-C. Lin et al. in the research article titled "Construction Database-Supported and BIM-Based Interface Communication and Management: A Pilot Project", propose a platform for the communication and management of interfaces (CMI) based on BIM that improves the quality of management in construction projects. The study presented by X. Chen et al. in the research article titled "Ontology-Based Representations of User Activity and Flexible Space Information: Towards an Automated Space-Use Analysis in Buildings" extends the current research on activity ontologies in order to capture flexible space-use patterns for user activities, and develops a new space ontology by abstracting the information related to both flexible and nonflexible spaces.

F. Rodrigues et al. in "Development of a Web Application for Historical Building Management through BIM Technology" demonstrate the necessity of the development and implementation of a strategy of intervention, which contributes to the preservation and maintenance of heritage, through the application of a management system able to answer this need in a reliable process. The work presented and the work analysed in the literature review show that Historical Building Information Modeling (HBIM) applications are often needed to jointly perform different kinds of analyses and to properly connect the related environments and formats; thus, it is clear why there is a need to focus the development of HBIM applications with a heterogeneous multimodels' interoperability with a standardized approach.

Y. Jeong in "A Study on the BIM Evaluation, Analytics, and Prediction (EAP) Framework and Platform in Linked Building Ontologies and Reasoners with Clouds" concludes that there has been less focus on the connectivity and convergence of multiple types of BIM data or even the connectivity among non-BIM data, such as natural language and image/video data. The research contributes by introducing an ontology to enable user-oriented object definition and operation with example cases.

3. Conclusions

The scope of the special issue proved to be appealing to researchers from all over the world. Papers from 12 countries, located in 5 continents, were published. The main research themes reported in this special issue revolve around interorganizational and cross-disciplinary collaboration, BIM adoption in SMEs, benchmarking the BIM use level, BIM technology integration with web technologies and AR technologies, BIM-based digital fabrication, and HBIM applications.

Conflicts of Interest

The editors declare that they have no conflicts of interest regarding the publication of this special issue.

Acknowledgments

The guest editors express their gratitude to Advances in Civil Engineering, for offering an academic platform for researchers to contribute and exchange their recent findings concerning BIM applications in the construction industry. They would like to thank the authors who have submitted manuscripts to this special issue and the referees who have put in time and effort generously to review each paper in a timely and professional manner. The lead editor particularly thanks all the editors for their contribution in reviewing and assigning reviews for the submitted manuscripts.

Tatjana Vilutiene
M. Reza Hosseini
Eugenio Pellicer
Edmundas K. Zavadskas

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 5290690, 19 pages
https://doi.org/10.1155/2019/5290690

Review Article

Building Information Modeling (BIM) for Structural Engineering: A Bibliometric Analysis of the Literature

Tatjana Vilutiene,[1] **Diana Kalibatiene**,[2] **M. Reza Hosseini**,[3] **Eugenio Pellicer**,[4] **and Edmundas Kazimieras Zavadskas**[5]

[1]*Department of Construction Management and Real Estate, Faculty of Civil Engineering, Vilnius Gediminas Technical University, Vilnius 10223, Lithuania*
[2]*Department of Information Systems, Faculty of Fundamental Sciences, Vilnius Gediminas Technical University, Vilnius 10223, Lithuania*
[3]*School of Architecture and Built Environment, Deakin University, Geelong 3220, Australia*
[4]*School of Civil Engineering, Universitat Politecnica de Valencia, 46022 Valencia, Spain*
[5]*Institute of Sustainable Construction, Faculty of Civil Engineering, Vilnius Gediminas Technical University, Vilnius 10223, Lithuania*

Correspondence should be addressed to Tatjana Vilutiene; tatjana.vilutiene@vgtu.lt

Received 30 January 2019; Revised 9 June 2019; Accepted 24 June 2019; Published 25 August 2019

Academic Editor: Eul-Bum Lee

Building information modeling (BIM) is transforming the way of work across the architecture, engineering, and construction (AEC) industry, where BIM offers vast opportunities for improving performance. BIM is therefore an area of great interest across the AEC industry in general and for the structural engineering field in particular. This paper is aimed at providing a broad picture of published papers that relate BIM with structural engineering. This overview will enhance understanding of the state of the research work on this subject, drawing upon bibliometric analysis of 369 papers. Findings provide an updated picture of how now-available studies that link BIM developments and applications in structural engineering are distributed chronologically, across journals, authors, countries, and institutions. Detailed analyses of citation networks present the cooccurrence map of keywords, citation patterns of journals and articles, the most cited journals, and the top 15 most cited articles on BIM in the area of structural engineering. Discussions demonstrate that research on BIM applications for structural engineering has been constantly growing with a sudden increase after 2014. This study reveals that research attempts on this area have been dominated by exploring generic issues of BIM like information management; however, technical issues of structural engineering, to be resolved through BIM capabilities, have remained overlooked. Moreover, the research work in this area is found to be conducted largely in isolation, comprising disjointed and fragmented research studies. Gaps and important areas for future research include modeling of structural components, automation of the assembly sequence, planning and optimization of off-site construction, and dynamic structural health monitoring.

1. Introduction

Building information modeling (BIM) is becoming increasingly popular in the architecture, engineering, and construction (AEC) sector [1–3]; research shows that BIM has the potential to make changes to the way the AEC industry operates [4, 5]. Analyzing the feedback on the benefits associated with the use of BIM on projects is still a matter of investigation [6]. There is however evidence in the literature to acknowledge the advantages of BIM for various areas and disciplines across the AEC supply chain [7, 8]; BIM incorporates software and information processing procedures for designing, documenting, visualizing, and reporting on buildings and other facilities in integration with policies, standards, regulations, etc. [2]. It helps AEC specialists in visualizing a future building in a virtual environment, planning the forthcoming construction processes, and identifying any potential design, construction, or operational issues [1]. Such benefits can add value to the practices of all the disciplines involved, including that of civil engineering, in general, and structural engineering, in particular [9–12].

There have been some in-depth reviews on BIM in general [9, 13–15] and studies that have dealt with specific fields like transportation infrastructure, heritage buildings [16], civil infrastructure maintenance [17], collaborative management [18–20], health and safety [21–23], contractors [10], and academics aspects [24, 25]. Research on the integration of BIM within civil engineering is still in its infancy [9]. Few researchers have focused on civil engineering in particular [26]. Within the civil engineering field, a review run on the BIM literature reveals that some publications like that of Hunt [27] and Bartley [12] have promoted the benefits of BIM for structural engineers. No scholarly work is found with a focus on analyzing the now-available literature on the applications of BIM for structural engineering. Synthesizing the existing literature to raise awareness of the state of affairs of research and spot the gaps to be addressed by future studies is, however, an essential step in advancing the body of knowledge of any field of the study [9, 23]. Various types of review studies can be carried out to address this gap. Despite the undoubted value, an in-depth critical review of the content of existing studies can be prone to subjectivity and is restricted because of their incapability in producing a replicable broad picture of the field [28, 29]. As asserted by Markoulli et al. [30], manual reviews provide a picture of the "trees" but fail in offering a broad overview of the "forest." Since this paper is aimed at providing a broad picture of published academic papers that relate BIM with structural engineering, authors have not applied the content analysis technique for all papers in search results but have analyzed the content of the papers qualitatively.

With the above in mind, this study is targeted at conducting a scientific literature review through a bibliometric analysis of BIM papers related to structural engineering published between 2003 and 2018 (both included). This review, as well as the subsequent analysis, is focused only on scientific journal papers (included in the Scopus database); trade journals and professional magazines are not included here. Detailed analysis of the papers presents the coauthorship networks, the cooccurrence map of keywords, the citation network of journals, the citation network of articles, the list of the most cited journals, and the top 15 most cited articles on BIM in the area of structural engineering. It is deemed that this study contributes to the field in raising awareness of the following:

(1) The knowledge composition of BIM in structural engineering in the analyzed 16-year period
(2) Most recent studies and trends of applying the BIM methodology in structural engineering
(3) Dominant research topics on BIM-related applications in structural engineering
(4) Identifying gaps and defining future areas of research on the topic

The remainder of this paper is structured as follows: Section 2 provides a background on potential advantages and benefits of BIM for structural engineers. Section 3 provides an overview of existing review studies on BIM applications for various disciplines. Section 4 presents the methods used, followed by findings and results in Section 5. The key findings—literature gaps—are discussed and future areas for research are suggested in Section 6 prior to the concluding remarks in Section 7. This paper concludes with communicating the clear message of this study from a broad perspective.

2. BIM for Structural Engineers

Structural engineering comprises a wide range of skills and competencies that apply to all project types. This includes projects that entail minor slope strengthening, as well as large-sized structures of tall buildings [12, 31]. Structural engineers can create complex structural systems and are responsible for finding solutions for the efficient use of structural elements and materials in order to make a building and its systems safe, sustainable, and durable [32]. Usually, structural designs must be integrated with the outputs generated by other disciplines like architects and engineers of different building services [33, 34]. Other roles and responsibilities of structural engineers include supervising construction activities on-site and maintaining communication with manufacturers and suppliers to address production problems [35]. The complexity of the tasks, the required combination of many different competencies, and the abundance of different communication channels necessitate a reliable data exchange platform [19, 36]. That is, maintaining the quality of the final product requires tools that enable structural engineers to check the parameters of the system under development and verify the reliability of the information transmitted [25]. One available solution that provides all such capabilities is BIM [9, 12].

BIM models are 3D geometric encoded, in diverse proprietary formats with the potential to add time (4D) and cost data (5D) attached to them [37]. That is, the core concept of BIM relies on providing object-oriented digital representations of buildings in the form of data-rich models and enabling simulation and analysis of these models for design/construction/operation purposes [38]. Most vendors offer BIM software that incorporates the three required capabilities needed for structural engineering: geometry, material properties, and loading conditions for an analysis. These all can be derived directly from a BIM model, stored, edited, and applied by such BIM software. For example, Autodesk Revit can supplement the physical representation of the objects commonly used by structural engineers, and Tekla Structures allows users to specify the location of connection nodes on its objects and degrees of freedom and also has objects to model structural loads and load cases (see Sacks et al. [38] for details).

Moreover, using BIM in structural engineering can reduce the number of request for information (RFI) items from contractors and makes possible the visualization of design for clients and other stakeholders [39]. BIM can also provide all the stakeholders with the opportunity to explore various readily available alternatives and design scenarios [40, 41].

The digital models produced by structural engineers can be coupled with downstream activities, for manufacturing and assembly of structural elements as well as identifying coordination problems between structural elements and those of other disciplines [1, 34]. BIM can be a part of an effective solution for structural engineers in monitoring the health and life cycle performance of structural elements, seismic retrofitting optimization [42, 43], and risk assessment of structures [44]. Other applications of BIM for structural engineering include increasing its efficiency in modeling complex geological structures, generating shop drawings, and designing temporary elements and formwork [43, 45].

With the above in mind, structural design/analysis must be treated as one of the main areas of application for BIM, a point argued by Hosseini et al. [9]. This further justified the need for conducting this study.

3. Previous Discipline-Based Review Studies

Structural engineering is a subset of civil engineering [46]. Available studies have targeted different issues of civil engineering projects concerning BIM: developments of BIM implementations [13]; communication modes [47]; information management frameworks [10]; refurbishment of historic buildings using BIM [16, 48]; implementation of BIM to existing buildings [49]; sustainable buildings [8, 50]; BIM adoption in different civil infrastructure facilities [26]; roles and responsibilities of BIM practitioners [51]; conceptualization of a BIM-based facilities management framework [52, 53]; visualization technologies in safety management [21, 23]; data classifications [54]; BIM knowledge mappings [14]; BIM research categories [55]; application of laser scan technology [56]; challenges facing the facilities management sector [52, 57, 58]; application of semantic web technologies; issues and recommendations for BIM and life cycle assessment tools [59]; BIM and GIS [60]; green BIM [61]; collaboration in BIM networks [19]; transportation infrastructure; road infrastructure [62]; highway maintenance [17]; role of BIM in generating big data [37], etc. These studies have added much value to the BIM literature and have explored a wide range of fields associated with civil engineering. Civil engineering is however a broad field, with many subsets, as argued by Kosky et al. [46]. A list of major review studies that refer to BIM for civil engineering is tabulated in Table 1. As illustrated in Table 1, no review study has focused on BIM applications for structural engineering purposes. In fact, as argued by Hosseini et al. [9], BIM for structural engineering has remained an overlooked area in the extant literature, compared against other applications of BIM.

4. Research Methods

The research design for reviewing papers on BIM in structural engineering is displayed in Figure 1. The procedure begins with a brief review of published papers on BIM in Scopus, proceeds to a detailed review of the refined dataset of publications, and concludes by analyzing the data.

This research process, as illustrated in Figure 1, comprises the following steps:

(1) *Defining Research Questions*. Research questions are defined in this step. The scope of the research questions depends on the type of the study. Therefore, according to Merschbrock and Munkvold [68] and Arksey and O'Malley [69], this study is a scoping study and designed to examine the available journal articles and to determine the range of spreading and usage of BIM and new trends of BIM developments in structural engineering. The research question is formulated as "What is known from the existing literature about the applications of BIM methodology and tools in structural engineering?"

(2) *Defining the List of Search Sources*. The Scopus (https://www.scopus.com) database was chosen, given that compared against similar databases like Web of Science (WoS), Scopus covers a wider range of sources and is quicker in indexing them, and therefore, it is treated as the preferred database for bibliometric purposes.

(3) *Defining Search Query Based on Keywords.* Searching keywords and their meaningful combinations are defined as the following search query, using keywords: (BIM AND "Building Information Model*" AND struct*).

Other terms, like "digital model" and "3D modelling," can also be used in the search. However, adding such terms increases the number of results but does not make it more specific. The term "BIM" was omitted, given that as recommended by previous bibliometric studies on the BIM literature [9], including BIM can result in adding research items from nonconstruction contexts like chemistry and economics and increase the likelihood of unrelated studies being added to the dataset.

Therefore, they were excluded from the search. Moreover, using the special character* in the query results in finding different variations of the same concept; for example, usage of "model*" allows to extend the search by adding different variations, like "models," "modelling," and "modeling." This is also the case for "struct*"; that is, it finds "structure," "structural," etc.

(4) *Searching*. The searching process is performed according to the query defined in step 3, and the preliminary results are presented in Figure 2.

(5) *Assessing Quality of Results*. Quality of results is assessed here. According to Kitchenham et al. [70], there is no commonly agreed definition of "quality." Therefore, quality issues presented by Zhang et al. [71] were the basis for consideration.

(6) *Bibliometric Analysis of Search Results*. The bibliometric analysis technique is used as the primary analysis method, with the reason being this

Table 1: Summary of major review studies on BIM for civil engineering.

Source	Review period in years	Number of analyzed articles	Source of articles (databases)	Focus	Key findings
Abdirad [13]	2007–2014	97 (selected out of 322)	ASCE, Elsevier, Taylor & Francis, Emerald, and ITcon	BIM implementation assessment	Developments of BIM implementations; metric-based BIM assessment; gaps and limitations
Bradley et al. [10]	2000–2015	259	Scopus, Engineering Village, ScienceDirect, WoS	BIM for infrastructure	4 research gaps in infrastructure and BIM; an information management framework
Bruno et al. [48]	2007–2017	120, 86 of them with international impact, and 1 project	—	Historic BIM	Gaps in historic BIM; methodology for diagnosis of historic buildings using BIM
Cheng et al. [26]	2002–2014	171 case studies and 62 articles	—	BIM for civil infrastructure	Current practices of BIM adoption in different civil infrastructure facilities; research gaps and recommendations; evaluation framework
Davies et al. [51]	2007–2016	36 articles and BIM guides	—	Roles and responsibilities of BIM specialists	Definition of roles and responsibilities of BIM practitioners
Edirisinghe et al. [52]	1996–2016	46 (selected out of 207)	—	BIM in FM	Conceptualization of a BIM-based FM framework; determining the path of future research
Guo et al. [21]	2000–2015	78	WoS and ASCE Library databases	The use of visualization technology	Usage of visualization technologies in safety management
Kylili and Fokaides [63]	2005–2016	Actual European policies and legislation	European policies and legislation	Existing European policies and legislation for the built environment and the construction materials	Future trends in construction
Laakso and Nyman [54]	1997–2007	The first 11 years of research on standard 938	—	Research and BIM standardization	Classification of data
Li et al. [14]	2004–2015		WoS	BIM knowledge map	60 key research areas 10 key research clusters
Lopez et al. [64]	—	BIM software websites, articles, brochures, and videos	—	The readiness and development of 4D BIM	A BIM knowledge map; a review of different issues concerning the usability of 4D BIM; matrices for decision-making according to investment in BIM software
Olawumi et al. [55]	—	445	—	BIM research categories	BIM research categories in the project sectors; a visualization of the structure of the BIM literature
Pärn and Edwards [56]	1970–2015	—	—	Laser scanning, 3D modeling devices, modes of delivery, and applications within AECO	Hierarchy of laser scan devices; analysis of 3D terrestrial laser scan technology applications
Pärn et al. [57]	2004–2015	—	—	BIM for asset management within the AECO sector	Challenges facing the FM sector

Table 1: Continued.

Source	Review period in years	Number of analyzed articles	Source of articles (databases)	Focus	Key findings
Santos et al. [65]	2005–2015	381	—	BIM	New emerging areas in BIM research; topics related to the development of BIM tools
Soust-Verdaguer et al. [59]	—	—	—	LCA method for buildings based on BIM	Issues and recommendations for BIM and LCA tools
Zhao [15]	2005–2016	614	WoS	BIM	The most productive and cocited authors, countries, and institutions
Oraee et al. [19]	2006–2016	62	—	Collaboration in BIM-based construction networks	BIM-enabled projects have focused on technology, whilst project-related and managerial antecedents have remained underresearched
Martinez-Aires et al. [22]	1981–2016	76	WoS and Scopus	Occupational health and safety in building construction	BIM to improve safety in construction and identify potential hazards through 4D scheduling
Ganbat et al. [66]	2007–2017	526	WoS	BIM risk management in international construction	A framework of current research field; suggestions for future research directions
Jin et al. [67]		276	Scopus	Identifying research trends in the literature on BIM	A framework leading to needed research directions

Note. —: data not provided.

technique allows for an examination of the existing literature based solely on reported data, in which any potential for author bias is minimized, compared against conventional literature reviews that are prone to bias and subjective judgments [55]. The findings of studies based on bibliometric analysis are hence expected to provide a sound basis for the development of various hypotheses based on the observed trends extracted from published datasets for validation in future studies.

Various researchers, like Li et al. [14], Zhao [15], and Santos et al. [65], have used different science mapping tools, including VOSviewer, BibExcel, CiteSpace, CoPalRed, Sci2, VantagePoint, and Gephi, for analyzing, mapping, and visualization of bibliometric data. A detailed review of visualization tools is not the main aim of this paper, and hence, VOSviewer (http://www.vosviewer.com/) was used as the analysis tool, following the recommendations provided by Hosseini et al. [9]. VOSviewer generates a network from the given bibliographic data, i.e., a set of 369 articles. All networks consist of nodes and links. Nodes present documents (i.e., articles), sources (i.e., journals), authors, organizations, countries, or keywords. Nodes with a higher number of occurrences are bigger. Links present relationships among nodes. Thicker links present closer relationships among nodes. Closely related nodes are combined into clusters using the smart local moving algorithm presented by Waltman and Van Eck [72].

5. Results

5.1. Trend of Research. The results obtained from the bibliometric search demonstrate the trend of research on the topic, as illustrated in Figure 2. The number of publications on BIM for structural engineering has raised significantly from 2014 onwards, with two years of delay compared against the sudden increase in BIM research in 2012, as argued by Santos et al. [65]. This increase from 2012 onwards can be attributed to the 2011 mandate of the Government Construction Strategy of the United Kingdom on the use of Level 2 BIM on all public sector projects by 2016 [73]. There is a growing interest (see Figure 2 for the exponential growth of publications), acknowledging the necessity of further research in this area. This also highlights the importance of covering various areas related to this concept as topics for future research, as similarly argued by Hosseini et al. [9]. In fact, construction is composed of a wide range of loosely coupled disciplines [74–76], and the expansion of BIM across the construction supply chain has been sluggish [58]. Therefore, the number of studies on structural engineering and BIM is quite low; compared with the results obtained by

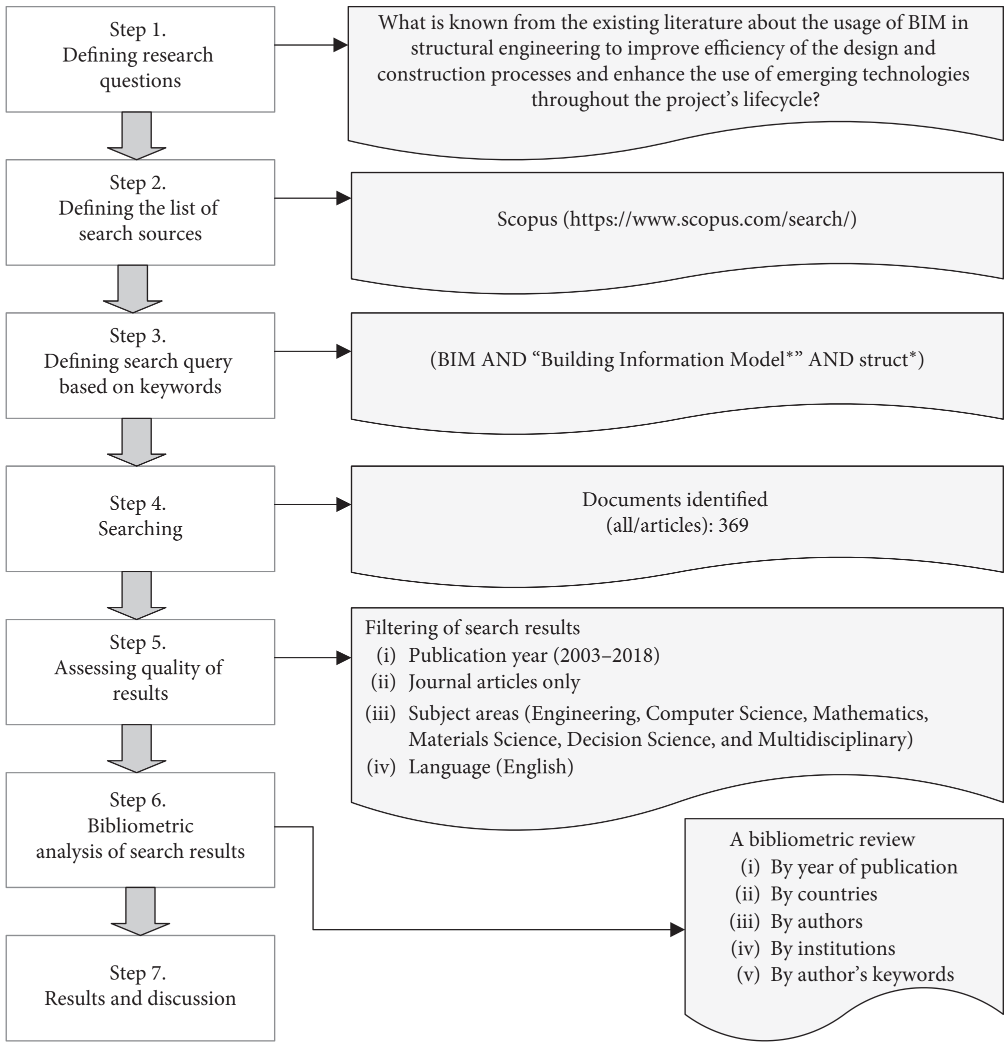


Figure 1: Research design for bibliometric analysis of retrieved papers.

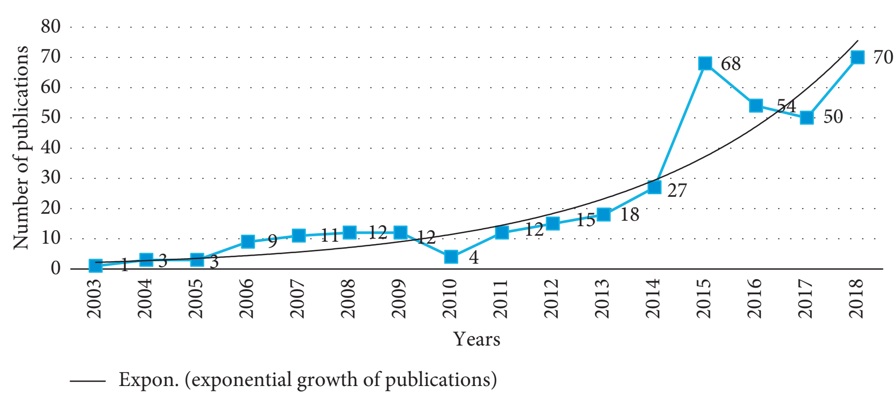


Figure 2: Variations in the number of BIM publications in the area of structural engineering.

Hosseini et al. [9], less than 20% of studies on BIM referred to structural engineering applications. This acknowledges the claims in the literature about the lack of attention paid to structural engineering in the BIM literature [9, 77, 78].

5.2. Coauthorship Networks. Identifying existing research collaboration networks on a topic has several advantages: (1) the awareness can facilitate access to funds, and needed, (2) the awareness will result in higher productivity, and (3) the awareness assists investigators to reduce silo-based and isolated research activities with boosting scholarly communications [79]. In Figure 3, a coauthorship network of authors is generated from the core dataset, as a result of which VOSviewer detects 836 authors. In Figure 3, a minimum of three

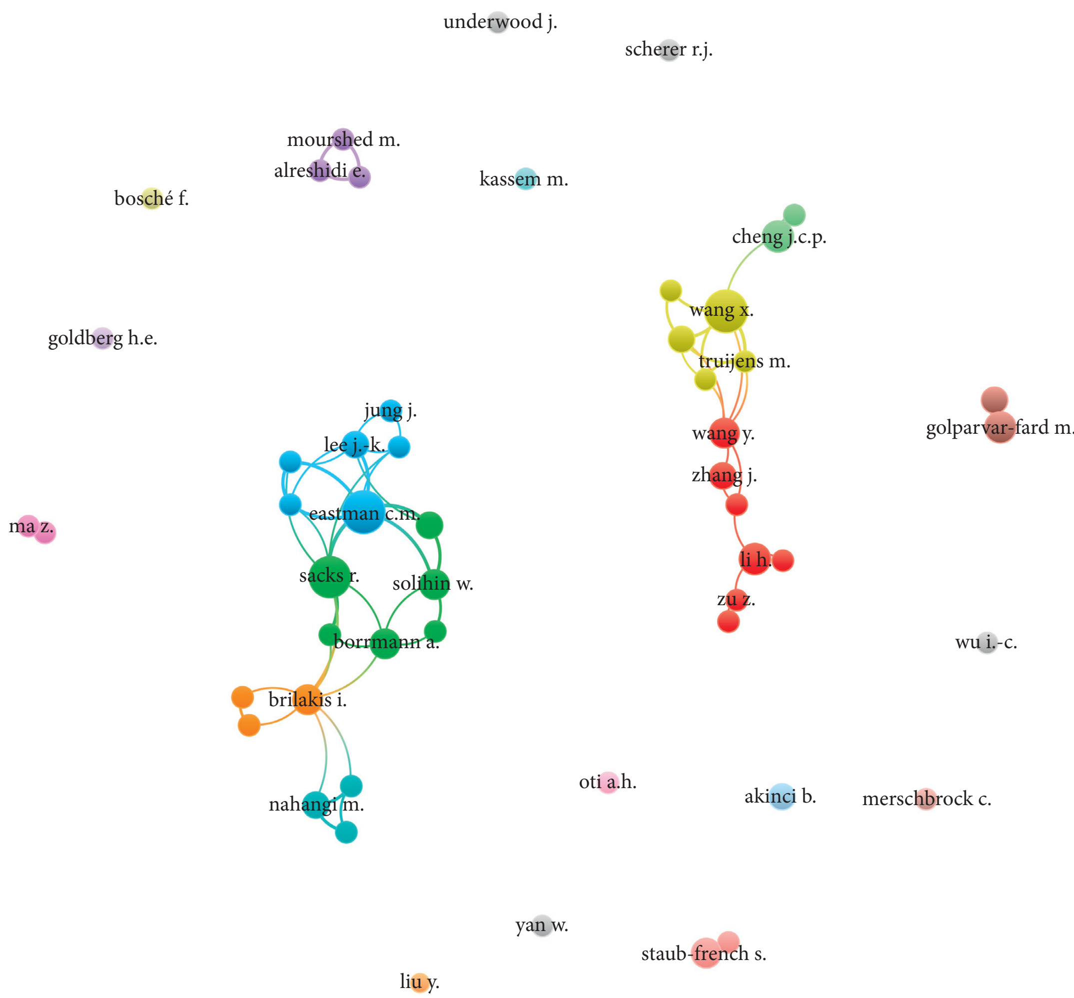


Figure 3: Coauthorship network of authors.

Table 2: The most active authors, whose number of articles focusing on BIM for structural engineering exceeds three.

Author	Number of articles	% of articles	Number of citations
C. M. Eastman	**11**	**13.75**	**704**
R. Sacks	**10**	**12.50**	**476**
X. Wang	**10**	**12.50**	**396**
M. Golparvar-Fard	6	7.50	278
A. Borrmann	5	6.25	46
I. Brilakis	5	6.25	172
S. Staub-French	5	6.25	31
B. Akinci	**4**	**5.00**	**318**
K. K. Han	4	5.00	155
L. Hou	4	5.00	93
J.-K. Lee	**4**	**5.00**	**299**
Y.-C. Lee	4	5.00	42
M. Nahangi	4	5.00	105
W. Solihin	4	5.00	33
Total	80	100	

Bold values depict the most cited authors in the set of leading authors in a group of coauthorship.

documents per author were chosen. After applying VOS-viewer algorithms, 52 authors were obtained. Figure 3 depicts eleven collaboration networks of authors in isolated groups and ten single authors disconnected from the network.

Authors with strong relationships and more articles are set as leading authors in a group of coauthorship. The most active authors, having more than three published articles, are presented in Table 2.

Ranking authors by the number of citations is different from ranking by the number of articles. Citations offer an indication of prominence, as a widely accepted measure for ranking the influence level of authors [80]. Therefore, a network of authors based on their citations was analyzed (see Figure 4). In Figure 4, a minimum of 10 citations of an author were chosen to make the analysis manageable. After applying VOSviewer algorithms, the result of the citation network of 49 authors is obtained. The most cited five authors are as follows: Eastman (704 citations), Sacks (476 citations), Wang (396 citations), Akinci (318 citations), and Lee (299 citations).

In view of the outcomes from Figures 3 and 4, several findings are worth mentioning. First, some large collaboration networks contribute to a major part of research on BIM in structural engineering, in the form of a "linked research enterprise," as termed by Newman [81].

Though presenting a promising picture, this also demonstrates that a major part of research on BIM in structural engineering is dominated by several researchers in a closed circle, calling for more investigation from other authors outside the identified research circle.

Second, a clear intellectual isolation from the mainstream of research on the topic is illustrated, where those who do not belong to the existing clusters form very small and disconnected clusters disjointed from the remaining parts of the network. This calls for more effort to integrate the existing disconnected clusters into one large linked research enterprise, not dominated by few investigators in a closed circle.

A coauthorship network of countries generated from the core dataset presented is illustrated in Figure 5.

A set of 50 countries is identified by VOSviewer (see Figure 5). After applying VOSviewer algorithms, the result of 26 countries is obtained. Finland, India, Norway, Sweden, and Taiwan have no interconnections with other countries; therefore, they are not presented in Figure 5. However, as can be seen in Table 3, the distribution of countries according to the number of citations differs. Here, the five leading countries are United States (2074 citations), United Kingdom (968 citations), South Korea (941 citations), Australia (656 citations), and China (592 citations), which were also referred by Jin et al. [82], as the current leaders in BIM adoption. This shows that many countries, including European countries (Germany, Italy, France, Netherlands, Spain, and Belgium), have had technological advancements in terms of applying BIM for various civil engineering purposes. That said, research activities in these countries and the level of influence of investigators from these countries in facilitating the integration of structural engineering with BIM have a noticeable gap with those in the five leading countries in the field, as discussed.

Table 4 introduces the top organizations that have published more than five papers. As can be seen, the most active four organizations are the Georgia Institute of Technology (16 articles), Curtin University (14 articles), Tsinghua University (13 articles), and Technion-Israel Institute of Technology (10 articles). This also reiterates the findings as discussed: other than few leading countries, institutions in other countries, even in countries with advanced BIM technology like European countries, have overlooked the importance of conducting research to facilitate and expedite the permeation of BIM-based structural engineering and stand far away from their counterparts in leading countries identified in Figure 4.

5.3. Cooccurrence Network. The cooccurrence analysis is usually performed using keywords, to present the main content of articles and the range of researched areas in any domain of the study [83]; it provides a picture of a domain, main areas of research, and trends of development. The cooccurrence analysis of the keyword network is performed using authors' keywords. VOSviewer creates the keyword network by considering the closeness and strength of existing links. The closeness and strength are calculated from the number of publications, in which both keywords have occurred together [80].

VOSviewer identified 2869 keywords from the initial set of 369 articles. Applying VOSviewer algorithms and limiting the minimum number of occurrences of a term to five times, the result was obtained from 147 keywords. The generated set of keywords must be refined again. That is, VOSviewer is capable of identifying synonyms and words with identical meaning, even with different orthography, like "modelling" and "modeling" and "technology" and "technologies." Moreover, similar keywords, like BIM, and building information model have the largest number of occurrences, given the nature of the topic at hand [9]. Therefore, in order to avoid distortion of the results, the resultant set of keywords was refined to omit such unnecessary items in the list. The refining procedure includes the following steps following the lessons by Hosseini et al. [9]:

(i) Elimination of terms related to BIM and having the same meaning, like "BIM," "building information model," and "building information modelling." The primary search of articles was made according to those terms, and it is natural that these terms will be repeated in each analyzed paper and will have the highest number of occurrences and total link strength calculated by VOSviewer.

(ii) Elimination of generic terms, like "construction industry," "architectural design," and "information theory," since those terms have the highest number of occurrences and total link strength, calculated by VOSviewer, because of searching query specifics in this area.

Moreover, as can be seen from Figure 6, the keyword map is visualized using various colors to show the chronological order of items.

In Figure 6, the most occurred keywords are presented. From Figure 6 and Table 5, the most occurred keywords in three periods are presented next. In the period 2010–2012 (colored in blue), the most popular keywords are "project management," "three dimensional," "productivity,"

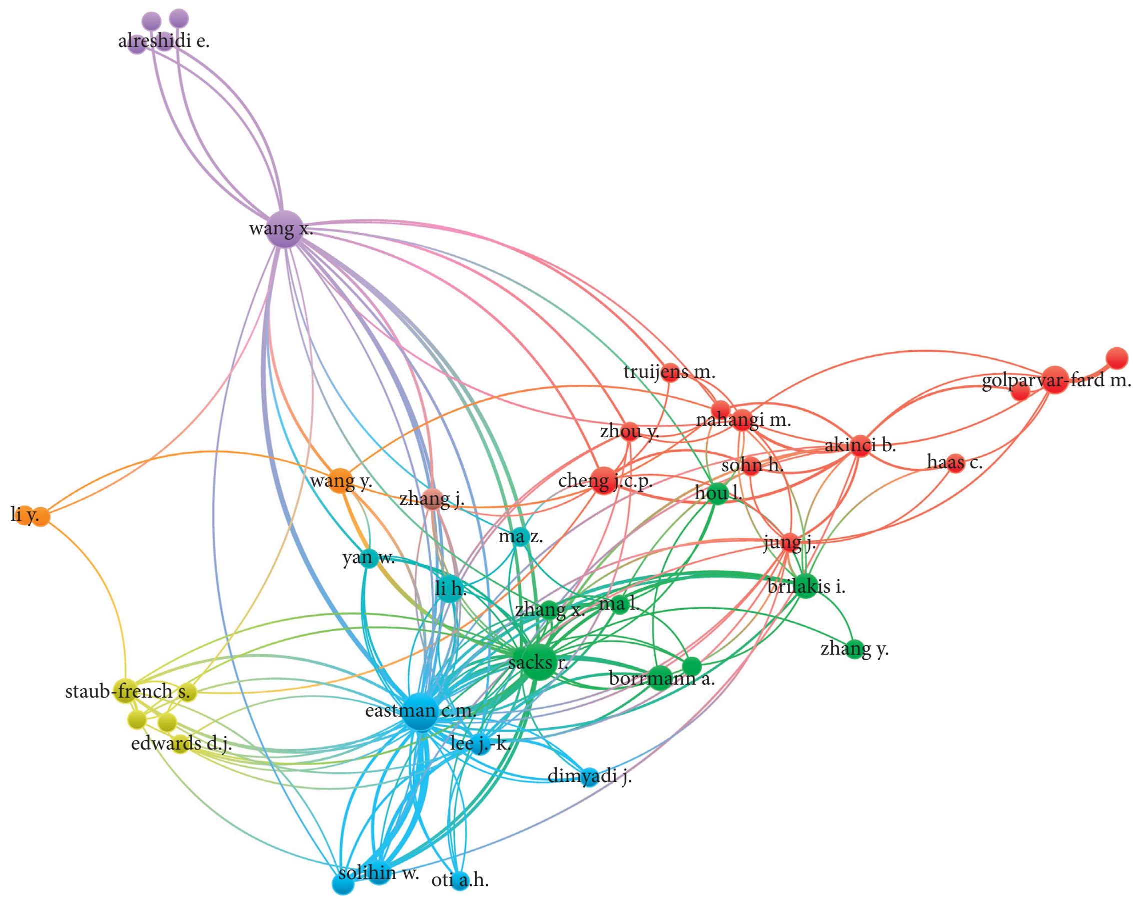


Figure 4: Citation network of authors.

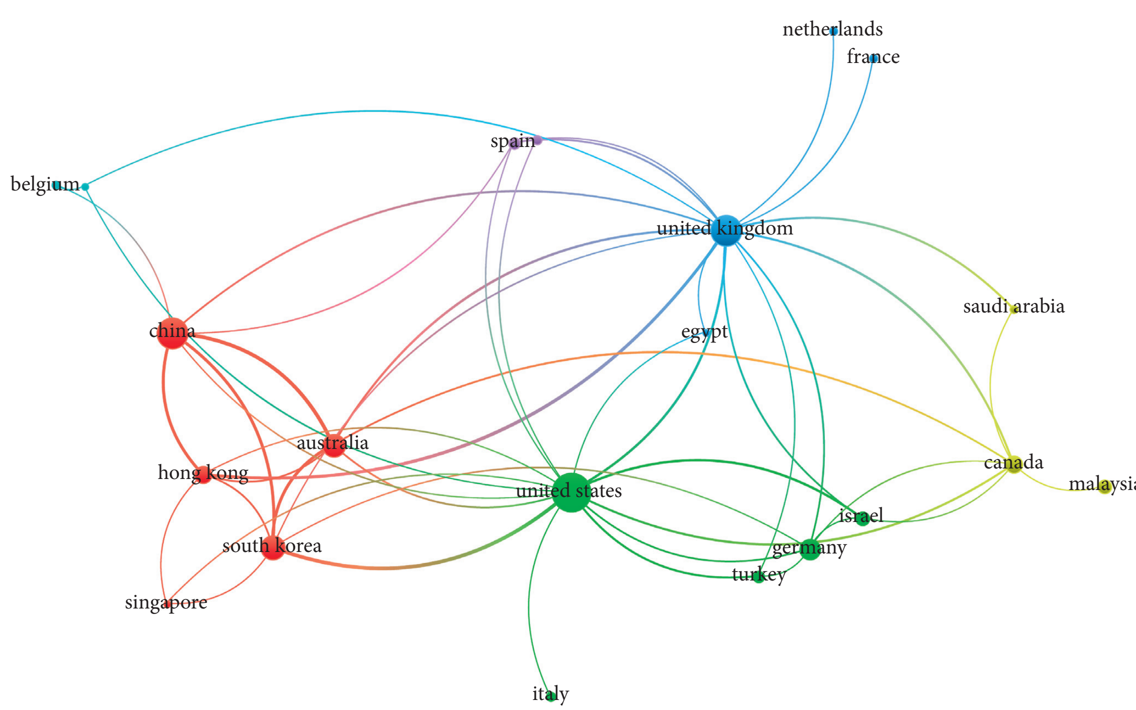


Figure 5: Coauthorship network of countries.

Table 3: The most active countries, where the number of articles exceeds or equals 5 (Scopus, December 2018).

Country	Number of articles	% of articles	Number of citations
United States	**87**	**20**	**2074**
United Kingdom	**57**	**13**	**968**
China	**55**	**13**	**592**
South Korea	**34**	**8**	**941**
Australia	**30**	**7**	**656**
Germany	25	6	272
Canada	19	4	316
Hong Kong	18	4	201
Israel	11	3	477
Malaysia	11	3	34
Taiwan	9	2	41
Spain	8	2	258
Turkey	8	2	231
Ireland	6	1	155
Italy	6	1	82
Finland	6	1	71
India	6	1	42
Norway	5	1	39

Table 4: The most active organizations, whose number of articles exceeds and equals 5.

Organizations	Number of articles	% of articles
Georgia Institute of Technology (United States)	**16**	**3.87**
Curtin University (Australia)	**14**	**3.39**
Tsinghua University (China)	**13**	**3.15**
Technion-Israel Institute of Technology (Israel)	**10**	**2.42**
University of Salford (United Kingdom)	9	2.18
Hanyang University (South Korea)	9	2.18
Kyung Hee University (South Korea)	8	1.94
Hong Kong University of Science and Technology (Hong Kong)	8	1.94
Hong Kong Polytechnic University (Hong Kong)	8	1.94
Cardiff University (United Kingdom)	8	1.94
University of Illinois at Urbana-Champaign (United States)	6	1.45
University of Waterloo (Canada)	6	1.45
Technical University of Munich (Germany)	6	1.45
Texas A&M University (United States)	6	1.45
Carnegie Mellon University (United States)	6	1.45
University of Cambridge (United Kingdom)	6	1.45
Pennsylvania State University (United States)	5	1.21
The University of British Columbia (Canada)	5	1.21
Yonsei University (South Korea)	5	1.21
University of New South Wales (UNSW) (Australia)	5	1.21

The bold values depict the most active four organizations.

"computer aided design," "database systems," "algorithms," "software design," "virtual reality," "standards," etc. The most occurred keywords in the period from 2013 to 2015 (colored in green) are "information systems," "information management," "industry foundation classes," "life cycle," "interoperability," "decision making," "energy efficiency," "semantics," etc. The most occurred keywords in the period 2016–2018 (colored in yellow) are "simulation," "automation," "data handling," "point cloud," "object detection," "cost benefit analysis," "risk assessment," "efficiency," "model view definition," etc. Arranging the keywords according to the citation score (see "Average citations" column in Table 5) results in generating a slightly different picture. That is, the popularity of terms according to the citation score in the three periods is as follows:

(i) 2010–2012: "in-buildings," "three dimensional," "productivity," "concrete construction," "computer aided design," "database systems," "algorithms," "software design," "virtual reality," etc.

(ii) 2013–2015: "model checking," "AEC," "planning," "scanning," "scheduling," "geometry," "interoperability," "design and construction," "collaboration," "precast concrete," etc.

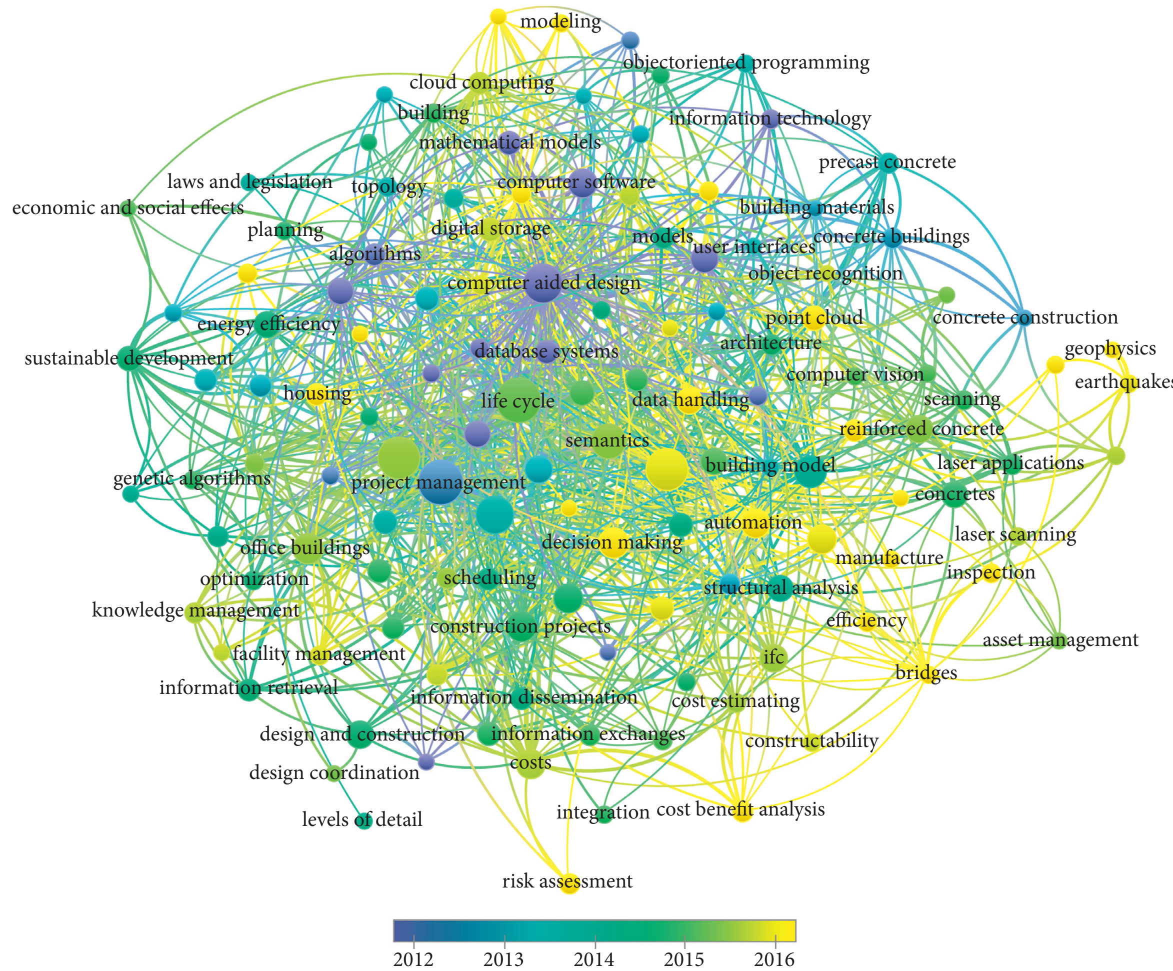


FIGURE 6: Cooccurrence map of keywords according to years.

(iii) 2016–2018: "simulation," "point cloud," "object detection," "automation," "classification," "model view definition (mvd)," "efficiency," "data handling," "inspection," "robotics," etc.

This analysis reveals the evolution of the BIM domain in the area of structural engineering has started with fundamental concepts like parametric design, computer simulations, and analysis of data structures, followed by a focus on the information management, interoperability, and collaboration in construction projects; the trend has shifted towards recent ideas of automation and big data analyses, decision-making, and development of knowledge management systems [75]. The interesting finding here is revealing the delayed attention paid to technical features and specific application of structural engineering within the BIM literature. That is, specialized applications of structural engineering are illustrated as isolated and small nodes in yellow color at the border of the circle of the network. This applies to all areas such as concrete construction, damage detection, floors, and retrofitting (see Figure 6). As such, research on BIM has been largely concerned with generic issues of integrating BIM into structural engineering practice and addressing common barriers that hinder BIM implementation on projects. The

TABLE 5: Keyword analysis (Scopus, December 2018).

Keyword	Links	Occurrences	Average citations
2010–2012			
project management	91	38	11.37
three dimensional	138	33	33.59
computer aided design	95	28	22.96
software design	111	26	14.37
database systems	74	16	21.92
algorithms	47	9	20.44
productivity	35	7	26.86
virtual reality	28	7	19.71
standards	37	6	9.00
civil engineering	28	6	5.17
in-buildings	33	5	76.00
building materials	30	5	16.40
concrete construction	28	5	25.60
2013–2015			
architectural design	146	258	14.84
information systems	181	140	14.00
structural design	130	126	15.80
information management	274	87	15.36
industry foundation classes (ifc)	254	71	19.20
construction	122	44	18.94

Table 5: Continued.

Keyword	Links	Occurrences	Average citations
life cycle	95	38	10.68
design	96	33	13.12
interoperability	76	27	30.93
decision making	109	26	15.81
cost estimating	99	23	7.77
energy efficiency	91	22	5.68
semantics	81	22	19.32
concrete buildings	94	21	14.27
construction projects	69	18	17.56
sustainable development	75	17	14.84
structural optimization	70	17	13.51
office buildings	63	17	27.53
visualization	52	16	15.31
laser applications	75	14	27.71
reinforced concrete	58	14	6.21
design and construction	51	14	29.93
structural analysis	55	13	8.62
facility management	79	12	27.73
AEC	58	11	50.55
digital storage	57	10	13.10
building codes	49	10	11.80
construction management	48	10	14.70
product design	48	10	4.60
data visualization	44	10	11.20
application programs	49	9	5.00
scheduling	48	9	38.11
intelligent buildings	46	9	19.56
model checking	43	9	62.00
cloud computing	38	9	20.78
information retrieval	35	9	10.78
ontology	48	8	16.50
quality control	47	8	15.38
precast concrete	41	8	28.50
knowledge management	39	8	13.00
architecture	37	8	22.50
artificial intelligence	45	7	14.71
building components	44	7	13.43
building	34	7	17.71
scanning	33	7	48.43
topology	30	7	12.71
compliance control	30	7	6.71
social networking	29	7	17.43
collaboration	27	7	28.71
cost engineering	44	6	16.00
specifications	42	6	9.67
genetic algorithms	39	6	21.50
software testing	37	6	13.67
planning	36	6	50.17
object oriented programming	35	6	11.50
historic preservation	32	6	18.00
damage detection	29	6	10.67
integration	28	6	8.00
earthquakes	26	6	4.67
walls (structural partitions)	25	6	43.67
constructability	21	6	12.17
software prototyping	41	5	14.40
user interfaces	36	5	17.00
geometry	29	5	32.20
conceptual design	28	5	12.20
economic and social effects	27	5	16.00
search engines	27	5	5.40
laws and legislation	26	5	4.60
levels of detail	25	5	26.40
floors	25	5	51.00
design coordination	23	5	21.40
asset management	13	5	8.80
2016–2018			
simulation	62	18	40.19
automation	77	16	27.88
data handling	65	13	7.54
point cloud	43	11	37.45
housing	47	9	9.89
maintenance	46	9	4.67
cost benefit analysis	28	8	4.88
risk assessment	25	8	4.88
efficiency	38	7	8.43
model view definition (mvd)	33	7	11.86
human resource management	32	7	17.86
classification	44	7	13.00
inspection	32	7	7.43
bridges	34	6	6.67
information modeling	33	6	6.50
manufacture	22	6	2.67
geophysics	21	5	3.20
big data	26	5	5.80
robotics	16	5	7.20
object detection	61	10	32.70

specialized and technical capabilities of BIM in various areas of structural engineering are hardly studied. The existing ones also remain isolated efforts disjointed from the main body of the BIM literature. This shows that the body of knowledge on the capabilities of BIM for integration with structural engineering practices is in its infancy. This can be explained in view of the fact that structural engineers still remain unsure of the risks and/or benefits of using BIM in performing their day-to-day activities and hence are uncertain of the potential to redesign their practices to align with the BIM methodology [84]. Moreover, the findings demonstrate fragmented and loosely coupled efforts in the absence of a coherent strategy or vision for integration of BIM into the structural engineering domain, and as a result, further research on these areas is much needed [9, 12, 78].

5.4. Citation Network. Analysis of citation networks determines cocitation of journals and documents, demonstrating an analysis of the number of times papers cite each other [9]. A journal network was generated using the dataset; 116 journals were detected by VOSviewer. After applying VOSviewer algorithms and limiting the minimum number of citations of a source to 50, the results pulled out 13 journals to form the main citation network (see Figure 7).

As it can be seen in Table 6, the most cited five journals are Automation in Construction (2374 citations, 82 articles),

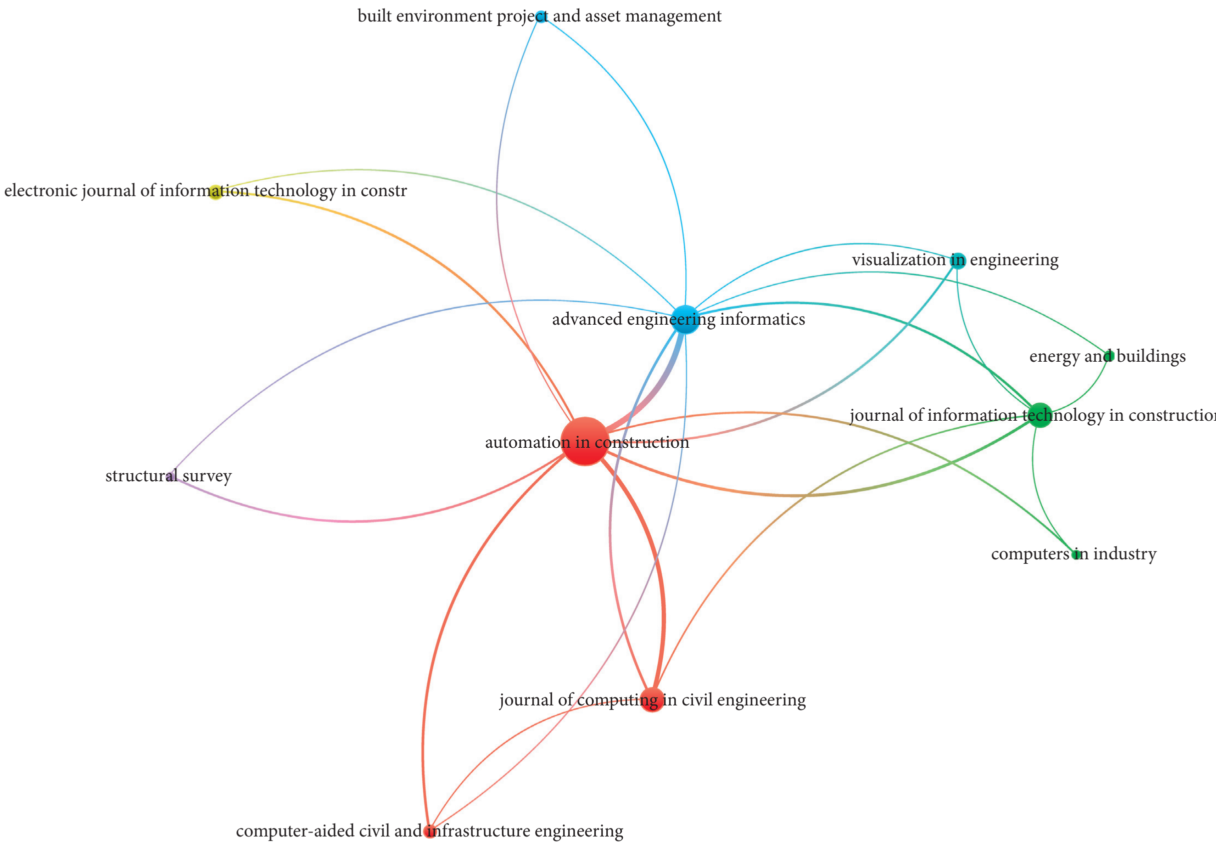


Figure 7: Citation network of journals.

Advanced Engineering Informatics (697 citations, 29 articles), Journal of Information Technology in Construction (337 citations, 28 articles), Journal of Computing in Civil Engineering (295 citations, 21 articles), and Visualization in Engineering (95 citations, 9 articles).

The citation network of articles is presented in Figure 8. After applying VOSviewer algorithms and limiting the minimum number of citations of an article to 15, the results are shown in the form of a network with 85 articles as its nodes. Of these, only 55 articles have cited each other.

Eliminating self-citation in Scopus, an overall view emerges that slightly differs from that of Figure 8 (see Table 7). The most cited four articles are as follows: Zhang et al. [85] (198 subtotal and 225 total citations), Xiong et al. [86] (195 subtotal and 220 total citations), Singh et al. [87] (122 subtotal and 186 total citations), and Lee et al. [88] (77 subtotal and 167 total citations).

Table 6: The most cited journals.

Journal	Number of citations*	Number of articles	% of articles
Automation in Construction	**2374**	**82**	**22.22**
Advanced Engineering Informatics	**697**	**29**	**7.86**
Journal of Information Technology in Construction	**337**	**28**	**7.59**
Journal of Computing in Civil Engineering	**295**	**21**	**5.69**
Visualization in Engineering	**95**	**9**	**2.44**
Construction Innovation	48	7	1.90
Computer-Aided Civil and Infrastructure Engineering	79	6	1.63
Built Environment Project and Asset Management	57	5	1.36

*Journals cited more than 40 times are included.

6. Gaps and Future Areas for Research

The analysis of results reveals that research on the topic of BIM in structural engineering has been an area experiencing significant growth, confirming the importance of applying BIM in structural engineering [12, 84]. This growth, however, is merely a reflection of the growth of the overall number of articles on BIM triggered by the 2011 mandate of the Government Construction Strategy of the United Kingdom [73]; while the noticeable increase in BIM research appears in 2012 [9, 65], structural engineering and BIM, as a topic, has come to the fore only after 2014. Previous studies have identified similar delays in conducting research on various BIM areas, where evidence refers to the delay for infrastructure, people side, and managerial areas of BIM [18]. This study highlights an analogous delay in research on structural engineering, revealing it as an area with major potential for implementing BIM. With the above in mind, this study, as an original insight provided, reveals that the now-available scientific literature on applications of BIM in

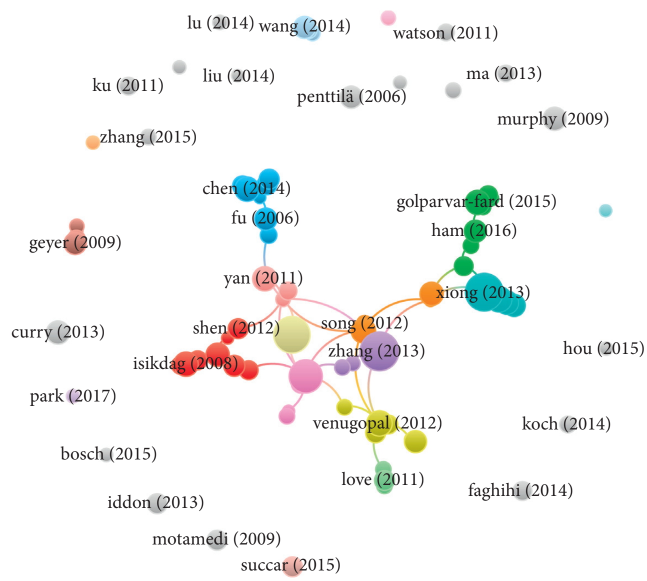


Figure 8: Citation network of articles.

Table 7: The most cited articles on BIM in the area of structural engineering excluding self-citation.

Year	Reference	2015	2016	2017	2018	Subtotal (2015–2018)	Total*
2013	*Zhang et al. [85]*	**29**	**47**	**59**	**60**	**198**	**225**
2013	*Xiong et al. [86]*	**38**	**40**	**52**	**60**	**195**	**220**
2011	*Singh et al. [87]*	**14**	**24**	**43**	**37**	**122**	**186**
2006	*Lee et al. [88]*	**20**	**16**	**19**	**20**	**77**	**167**
2015	Pătrăucean et al. [89]	4	16	23	39	84	84
2008	Isikdag et al. [90]	6	11	15	12	44	82
2011	Yan et al. [91]	13	10	15	18	56	77
2014	Chen and Luo [92]	8	15	23	29	75	75
2009	Jeong et al. [93]	9	5	13	8	35	75
2012	Steel et al. [94]	16	10	18	10	57	74
2012	Venugopal et al. [95]	11	19	13	8	54	72
2009	Murphy et al. [96]	4	10	18	23	56	68
2008	Arayici [97]	9	11	13	13	47	68
2015	Golparvar-Fard et al. [98]	8	17	13	18	56	66
	Total count	428	685	1057	1310	3594	4439

*All years covered by Scopus.

structural engineering has been mainly concerned with generic issues of BIM like information management. As a result, BIM has much unexplored capacity for solving complex technical issues in specialized areas of structural engineering, another evidence for the infancy of BIM applications in the civil engineering field [9] and, in particular, structural engineering applications.

Another novelty of this study lies in its approach to bring together various applications of BIM in structural engineering from isolated studies in the literature, in the chronological order. The outcome is a point of reference that showcases all these applications, as a readily available reference frame for researchers, as well as practitioners. Research studies refer to much unexploited potential for using BIM in structural engineering, in integration with a bulk of available technologies for information management like classification tools based on [9] ontology rules, cloud computing, laser scanning, visualization techniques, simulation software, etc. Interested readers are referred to Sacks et al. [38] for details.

As another contribution of this study (illustrated in Figure 9), the findings demonstrate the evolution of BIM developments in areas associated with structural engineering, starting from the development of standards for computer-aided design, database systems, algorithms, software tools, and approaches to rise productivity. These developments are followed by shifting the focus towards information management, interoperability, and decision-making, eventually moving to the automation of processes, big data analytics, and simulation practices [19]. As the outcome, gaps and important areas for future research are identified, a description of which is as follows.

Automated modeling is deemed an essential element of various key applications like progress monitoring, status

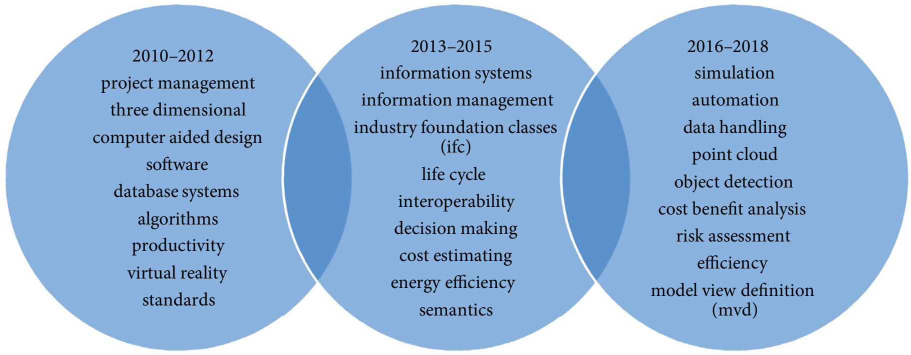


Figure 9: Evolvement directions of BIM in structural engineering.

assessment, and quality control. Therefore, an exponential growth of research efforts on automated construction progress monitoring is detected, in recent years.

The area, however, is still in its infancy [99]; that is, automated detection of structural elements within BIM models still is seen as a challenge, and hence, improving techniques and methods for accurate automated object identification—structural elements—within models is a ripe area for future studies [100].

With the sudden increase of interest in off-site construction—prefabrication—in many countries [101], increasing the prefabrication rate of precast concrete structures, automation of the assembly sequence and planning, and optimization must be topics important on the agenda within the domain of structural engineering [102]. With BIM in mind, future studies can target the unique characteristics of cast-in-place concrete in developing future versions of IFC, overlapping of structural elements, use of reinforcement bars, and the need for precision in loads and material considerations [103]. Automated creation of centralized accurate semantically rich as-built building information models of structural elements also remains a fertile area for future research, given various challenges that affect successful implementation of BIM for such purposes [104–107].

Dynamic structural health monitoring is another research area of paramount importance, to be considered for future investigation of BIM in the structural engineering domain. There is increasing demand for integration of BIM with data generated through sensors for live monitoring the health of structural elements [108]. Several ideas about automatic generation of BIM models of structural monitoring systems that include time-series sensor data that support dynamic visualization in an interactive 3D environment exist [109, 110], and the area remains in need of empirical studies to validate the proposed designs. These are hence future areas for research to promote the use of BIM in structural engineering.

7. Conclusions

This study is the first attempt in its kind in exploring the state of published research studies that link BIM with structural engineering. The area has attracted much interest, and some research efforts in the form of literature reviews are available in related fields like infrastructure engineering and civil engineering applications. Nevertheless, this study stands out. This is because this study offers a picture of the landscape of the body of BIM knowledge in relation to structural engineering, as an area that remains unexplored and unassessed. This study contributes to the field by diagnosing the problems of the literature from a holistic vantage point. It provides original insight into the issues revolving around technical aspects of structural engineering being overshadowed by challenges of BIM process implementation. This study also provides a point of reference to demonstrate what areas of BIM for structural engineering have been explored and what remain to be investigated, acting as an agenda for future research on the topic. In methodological terms, this study draws upon a quantitative analysis of citation networks, which involves minimal subjective judgment, making the findings reliable and reproducible. The findings presented contribute to the field by spotting the gaps to be addressed, trends to be redefined, and main areas of focus for future research. That is, the findings reveal that research on structural engineering applications of BIM is still in its infancy with many gaps; much remains yet to be done in making it an established domain of inquiry.

The clear message is that BIM-related issues like challenges of BIM implementation on projects have overshadowed the potential of BIM for structural engineering, and as such, existing studies have overlooked the technical issues of structural engineering to be resolved through the use of BIM. Moreover, the extant literature on the topic presents fragmented, isolated research efforts. And the isolation applies to the research subjects, active investigators, and their institutions, alike. These trends need reassessing and redefining, as highlighted by the findings of this study.

With the above in mind, future work—in the area of structural engineering and BIM—must target bringing in issues of structural engineering to be addressed and solved through applying BIM capabilities. Future research is needed through forming research collaborative networks that have enhancing dialogue, debate, and intracountry and intraorganization cross-fermentation of initiatives and ideas, as their priorities. These findings raise awareness and enhance understanding of the necessity of addressing the identified gaps and neglected areas within the BIM literature. This contributes to directing deeper, more carefully selected, research into the field and assists policy-makers and industry partners of research projects in their plans for supporting and funding.

Despite the contributions associated with this study, all research studies have limitations, and this study is no exception. First, the analysis only covered the literature in English, using a certain set of keywords for searching. Second, the analysis was based on the dataset retrieved from Scopus; hence, it is affected by the limitations of Scopus in terms of coverage. Therefore, the findings may not fully reflect the entire available corpus of the BIM literature. Furthermore, this study, because of space limitations, was focused on providing a broad picture of the available literature on BIM for structural engineering through a bibliometric analysis of citation networks and less concerned with an in-depth content analysis of available studies. Nevertheless, before the bibliometric analysis of citation networks, authors made an in-depth qualitative analysis of the retrieved papers. A complementary study to analyze the content of available studies remains a ripe area for research on the topic.

Data Availability

The data generated in this research are available from the corresponding author on request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] S. Azhar, "Building information modeling (BIM): trends. benefits. risks. and challenges for the aec industry," *Leadership and Management in Engineering*, vol. 11, no. 3, pp. 241–252, 2011.

[2] G. Wang and J. Song, "The relation of perceived benefits and organizational supports to user satisfaction with building information model (BIM)," *Computers in Human Behavior*, vol. 68, pp. 493–500, 2017.

[3] M. Hu, "BIM-enabled pedagogy approach: using BIM as an instructional tool in technology courses," *Journal of Professional Issues in Engineering Education and Practice*, vol. 145, no. 1, article 05018017, 2018.

[4] B. Dasović, M. Galić, and U. Klanšek, "Active BIM approach to optimize work facilities and tower crane locations on construction sites with repetitive operations," *Buildings*, vol. 9, no. 1, p. 21, 2019.

[5] P. Gholizadeh, B. Esmaeili, and P. Goodrum, "Diffusion of building information modeling functions in the construction industry," *Journal of Management in Engineering*, vol. 34, no. 2, article 04017060, 2018.

[6] M. Galić, V. Venkrbec, F. Chmelik, I. Feine, Z. Pučko, and U. Klanšek, "Survey of accomplishments in BIM implementation in Croatia, The Czech Republic, Germany and Slovenia," *E-GFOS*, vol. 8, no. 15, pp. 23–35, 2017.

[7] C. Boton and D. Forgues, "Practices and processes in BIM projects: an exploratory case study," *Advances in Civil Engineering*, vol. 2018, Article ID 7259659, 12 pages, 2018.

[8] Y. Liu, S. van Nederveen, C. Wu, and M. Hertogh, "Sustainable infrastructure design framework through integration of rating systems and building information modeling," *Advances in Civil Engineering*, vol. 2018, Article ID 8183536, 13 pages, 2018.

[9] M. R. Hosseini, M. Maghrebi, A. Akbarnezhad, I. Martek, and M. Arashpour, "Analysis of citation networks in building information modeling research," *Journal of Construction Engineering and Management*, vol. 144, article 04018064, 2018.

[10] A. Bradley, H. Li, R. Lark, and S. Dunn, "BIM for infrastructure: an overall review and constructor perspective," *Automation in Construction*, vol. 71, pp. 139–152, 2016.

[11] I. Kaner, R. Sacks, W. Kassian, and T. Quitt, "Case studies of BIM adoption for precast concrete design by mid-sized structural engineering firms," *Journal of Information Technology in Construction (ITcon)*, vol. 13, pp. 303–323, 2008.

[12] T. Bartley, "BIM for civil and structural engineers,"2017, BSI, London, UK, http://biblus.accasoftware.com/en/wp-content/uploads/sites/2/2017/10/BIM-for-Civil-and-Structural-Engineers.pdf.

[13] H. Abdirad, "Metric-based BIM implementation assessment: a review of research and practice," *Architectural Engineering and Design Management*, vol. 13, no. 1, pp. 52–78, 2017.

[14] X. Li, P. Wu, G. Q. Shen, X. Wang, and Y. Teng, "Mapping the knowledge domains of building information modeling (BIM): a bibliometric approach," *Automation in Construction*, vol. 84, pp. 195–206, 2017.

[15] X. Zhao, "A scientometric review of global BIM research: analysis and visualization," *Automation in Construction*, vol. 80, pp. 37–47, 2017.

[16] F. Rodrigues, J. Teixeira, R. Matos, and H. Rodrigues, "Development of a web application for historical building management through BIM technology," *Advances in Civil Engineering*, vol. 2019, Article ID 9872736, 15 pages, 2019.

[17] Z. Aziz, Z. Riaz, and M. Arslan, "Leveraging BIM and big data to deliver well maintained highways," *Facilities*, vol. 35, no. 13/14, pp. 818–832, 2017.

[18] Q. He, G. Wang, L. Luo, Q. Shi, J. Xie, and X. Meng, "Mapping the managerial areas of building information modeling (BIM) using scientometric analysis," *International Journal of Project Management*, vol. 35, no. 4, pp. 670–685, 2017.

[19] M. Oraee, M. R. Hosseini, E. Papadonikolaki, R. Palliyaguru, and M. Arashpour, "Collaboration in BIM-based construction networks: a bibliometric-qualitative literature review," *International Journal of Project Management*, vol. 35, no. 7, pp. 1288–1301, 2017.

[20] M. Oraee, M. R. Hosseini, D. J. Edwards, H. Li, E. Papadonikolaki, and D. Cao, "Collaboration barriers in BIM-based construction networks: a conceptual model," *International Journal of Project Management*, vol. 37, no. 6, pp. 839–854, 2019.

[21] H. Guo, Y. Yu, and M. Skitmore, "Visualization technology-based construction safety management: a review," *Automation in Construction*, vol. 73, pp. 135–144, 2017.

[22] M. D. Martínez-Aires, M. López-Alonso, and M. Martínez-Rojas, "Building information modeling and safety management: a systematic review," *Safety Science*, vol. 101, pp. 11–18, 2018.

[23] R. Jin, P. X. W. Zou, P. Piroozfar et al., "A science mapping approach based review of construction safety research," *Safety Science*, vol. 113, pp. 285–297, 2019.

[24] H. Abdirad and C. S. Dossick, "BIM curriculum design in architecture. engineering. and construction education: a

systematic review," *Journal of Information Technology in Construction*, vol. 21, pp. 250–271, 2016.
[25] Z. Xu, T. Huang, B. Li, H. Li, and Q. Li, "Developing an IFC-based database for construction quality evaluation," *Advances in Civil Engineering*, vol. 2018, Article ID 3946051, 22 pages, 2018.
[26] J. C. P. Cheng, Q. Lu, and Y. Deng, "Analytical review and evaluation of civil information modeling," *Automation in Construction*, vol. 67, pp. 31–47, 2016.
[27] C. A. Hunt, *The Benefits of Using Building Information Modeling in Structural Engineering*, Utah State University, Logan, Utah, 2013.
[28] M. Hammersley, "On "systematic" reviews of research literatures: a "narrative" response to evans & benefield," *British Educational Research Journal*, vol. 27, no. 5, pp. 543–554, 2001.
[29] R. Jin, J. Zuo, and J. Hong, "Scientometric review of articles published in ASCE's journal of construction engineering and management from 2000 to 2018," *Journal of Construction Engineering and Management*, vol. 145, article 06019001, 2019.
[30] M. P. Markoulli, C. I. S. G. Lee, E. Byington, and W. A. Felps, "Mapping human resource management: reviewing the field and charting future directions," *Human Resource Management Review*, vol. 27, no. 3, pp. 367–396, 2017.
[31] S. Chin, S. Yoon, C. Choi, and C. Cho, "RFID + 4D CAD for progress management of structural steel works in high-rise buildings," *Journal of Computing in Civil Engineering*, vol. 22, no. 2, pp. 74–89, 2008.
[32] M. Sun, W. J. Staszewski, and R. N. Swamy, "Smart sensing technologies for structural health monitoring of civil engineering structures," *Advances in Civil Engineering*, vol. 2010, Article ID 724962, 13 pages, 2010.
[33] A. Charleson, *Structure as Architecture*, Routledge, Abingdon, UK, 2006.
[34] Z. Pezeshki and S. A. S. Ivari, "Applications of BIM: a brief review and future outline," *Archives of Computational Methods in Engineering*, vol. 25, no. 2, pp. 273–312, 2018.
[35] O. P. Larsen and A. Tyas, *Conceptual Structural Design: Bridging the Gap between Architects and Engineers*, Thomas Telford, London, UK, 2003.
[36] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley & Sons, Hoboken, NJ, USA, 2011.
[37] M. Bilal, L. O. Oyedele, J. Qadir et al., "Big data in the construction industry: a review of present status. opportunities. and future trends," *Advanced Engineering Informatics*, vol. 30, no. 3, pp. 500–521, 2016.
[38] R. Sacks, C. Eastman, G. Lee, and P. Teicholz, "BIM for architects and engineers," in *BIM Handbook*, R. Sacks, C. Eastman, G. Lee, and P. Teicholz, Eds., John Wiley & Sons, Hoboken, NJ, USA, 2018.
[39] E. Papadonikolaki, R. Vrijhoef, and H. Wamelink, "The interdependences of BIM and supply chain partnering: empirical explorations," *Architectural Engineering and Design Management*, vol. 12, no. 6, pp. 476–494, 2016.
[40] A. Strafaci, "What does BIM mean for civil engineers? 2008, http://images.autodesk.com/adsk/files/what_does_BIM_mean_for_civil_engineers_ce_news_1008.pdf.
[41] S. Abrishami, J. Goulding, F. Pour Rahimian, and A. Ganah, "Virtual generative BIM workspace for maximising AEC conceptual design innovation," *Construction Innovation*, vol. 15, no. 1, pp. 24–41, 2015.
[42] A. Okakpu, A. GhaffarianHoseini, J. Tookey, J. Haar, A. Ghaffarianhoseini, and A. Rehman, "A proposed framework to investigate effective BIM adoption for refurbishment of building projects," *Architectural Science Review*, vol. 61, no. 6, pp. 467–479, 2018.
[43] M. Marzouk and M. Hisham, "Implementing earned value management using bridge information modeling," *KSCE Journal of Civil Engineering*, vol. 18, no. 5, pp. 1302–1313, 2014.
[44] V. Kasireddy, S. Ergan, B. Akinci, and N. S. Gulgec, "Visualization requirements of engineers for risk assessment of embankment dams," *Visualization in Engineering*, vol. 3, no. 1, p. 1, 2015.
[45] Y. Zhang, D. Zhong, B. Wu, T. Guan, P. Yue, and H. Wu, "3D parametric modeling of complex geological structures for geotechnical engineering of dam foundation based on T-splines," *Computer-Aided Civil and Infrastructure Engineering*, vol. 33, no. 7, pp. 545–570, 2018.
[46] P. Kosky, R. Balmer, W. Keat, and G. Wise, "Chapter 7—civil engineering," in *Exploring Engineering*, R. Balmer, W. Keat, and G. Wise, Eds., pp. 127–160, Academic Press, Boston, MA, USA, 3rd edition, 2013.
[47] S. Alsafouri and S. K. Ayer, "Review of ict implementations for facilitating information flow between virtual models and construction project sites," *Automation in Construction*, vol. 86, pp. 176–189, 2018.
[48] S. Bruno, M. De Fino, and F. Fatiguso, "Historic building information modelling: performance assessment for diagnosis-aided information modelling and management," *Automation in Construction*, vol. 86, pp. 256–276, 2018.
[49] R. Volk, J. Stengel, and F. Schultmann, "Building Information Modeling (BIM) for existing buildings—literature review and future needs," *Automation in Construction*, vol. 38, pp. 109–127, 2014.
[50] Y. Lu, Z. Wu, R. Chang, and Y. Li, "Building information modeling (BIM) for green buildings: a critical review and future directions," *Automation in Construction*, vol. 83, pp. 134–148, 2017.
[51] K. Davies, S. Wilkinson, and D. McMeel, "A review of specialist role definitions in BIM guides and standards," *Journal of Information Technology in Construction (ITcon)*, vol. 22, pp. 185–203, 2017.
[52] R. Edirisinghe, K. A. London, P. Kalutara, and G. Aranda-Mena, "Building information modelling for facility management: are we there yet?," *Engineering. Construction and Architectural Management*, vol. 24, no. 6, pp. 1119–1154, 2017.
[53] J. Matthews, P. E. D. Love, J. Mewburn, C. Stobaus, and C. Ramanayaka, "Building information modelling in construction: insights from collaboration and change management perspectives," *Production Planning & Control*, vol. 29, no. 3, pp. 202–216, 2018.
[54] M. Laakso and L. Nyman, "Exploring the relationship between research and BIM standardization: a systematic mapping of early studies on the IFC standard (1997–2007)," *Buildings*, vol. 6, no. 1, p. 7, 2016.
[55] T. O. Olawumi, D. W. M. Chan, and J. K. W. Wong, "Evolution in the intellectual structure of BIM research: a bibliometric analysis," *Journal of Civil Engineering and Management*, vol. 23, no. 8, pp. 1060–1081, 2017.
[56] E. A. Pärn and D. Edwards, "Vision and advocacy of optoelectronic technology developments in the AECO sector," *Built Environment Project and Asset Management*, vol. 7, no. 3, pp. 330–348, 2017.

[57] E. A. Pärn, D. J. Edwards, and M. C. P. Sing, "The building information modelling trajectory in facilities management: a review," *Automation in Construction*, vol. 75, pp. 45–55, 2017.

[58] M. Hilal, T. Maqsood, and A. Abdekhodaee, "A scientometric analysis of BIM studies in facilities management," *International Journal of Building Pathology and Adaptation*, vol. 37, no. 2, pp. 122–139, 2018.

[59] B. Soust-Verdaguer, C. Llatas, and A. García-Martínez, "Critical review of BIM-based LCA method to buildings," *Energy and Buildings*, vol. 136, pp. 110–120, 2017.

[60] Y. Song, X. Wang, Y. Tan et al., "Trends and opportunities of BIM-GIS integration in the architecture. engineering and construction industry: a review from a spatio-temporal statistical perspective," *ISPRS International Journal of Geo-Information*, vol. 6, no. 12, p. 397, 2017.

[61] A. Darko, A. P. C. Chan, X. Huo, and D.-G. Owusu-Manu, "A scientometric analysis and visualization of global green building research," *Building and Environment*, vol. 149, pp. 501–511, 2019.

[62] H. Y. Chong, R. Lopez, J. Wang, X. Wang, and Z. Zhao, "Comparative analysis on the adoption and use of BIM in road infrastructure projects," *Journal of Management in Engineering*, vol. 32, article 05016021, 2016.

[63] A. Kylili and P. A. Fokaides, "Policy trends for the sustainability assessment of construction materials: a review," *Sustainable Cities and Society*, vol. 35, pp. 280–288, 2017.

[64] R. Lopez, H.-Y. Chong, X. Wang, and J. Graham, "Technical review: analysis and appraisal of four-dimensional building information modeling usability in construction and engineering projects," *Journal of Construction Engineering and Management*, vol. 142, article 06015005, 2015.

[65] R. Santos, A. A. Costa, and A. Grilo, "Bibliometric analysis and review of building information modelling literature published between 2005 and 2015," *Automation in Construction*, vol. 80, pp. 118–136, 2017.

[66] T. Ganbat, H.-Y. Chong, P.-C. Liao, and Y.-D. Wu, "A bibliometric review on risk management and building information modeling for international construction," *Advances in Civil Engineering*, vol. 2018, Article ID 8351679, 13 pages, 2018.

[67] R. Jin, Y. Zou, K. Gidado, P. Ashton, and N. Painting, "Scientometric analysis of BIM-based research in construction engineering and management," *Engineering, Construction and Architectural Management*, 2019.

[68] C. Merschbrock and B. E. Munkvold, "A research review on building information modeling in construction—an area ripe for IS research," *Communications of the Association for Information Systems*, vol. 31, 2012.

[69] H. Arksey and L. O'Malley, "Scoping studies: towards a methodological framework," *International Journal of Social Research Methodology*, vol. 8, no. 1, pp. 19–32, 2005.

[70] B. Kitchenham, O. Pearl Brereton, D. Budgen, M. Turner, J. Bailey, and S. Linkman, "Systematic literature reviews in software engineering—a systematic literature review," *Information and Software Technology*, vol. 51, no. 1, pp. 7–15, 2009.

[71] H. Zhang, B. Kitchenham, and D. Pfahl, "Reflections on 10 years of software process simulation modeling: a systematic review," in *Proceedings of the International Conference on Software Process*, pp. 345–356, Springer, Beijing, China, October 2008.

[72] L. Waltman and N. J. Van Eck, "A smart local moving algorithm for large-scale modularity-based community detection," *European Physical Journal B*, vol. 86, no. 11, p. 471, 2013.

[73] Cabinet Office, "Government construction strategy," 2011, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachme_nt_data/file/61152/Government-Construction-Strategy_0.pdf.

[74] E. Papadonikolaki, "Loosely coupled systems of innovation: aligning BIM adoption with implementation in Dutch construction," *Journal of Management in Engineering*, vol. 34, article 05018009, 2018.

[75] T. O. Olawumi and D. W. M. Chan, "Building information modelling and project information management framework for construction projects," *Journal of Civil Engineering and Management*, vol. 25, no. 1, pp. 53–75, 2019.

[76] G. Mignone, M. R. Hosseini, N. Chileshe, and M. Arashpour, "Enhancing collaboration in BIM-based construction networks through organisational discontinuity theory: a case study of the new royal adelaide hospital," *Architectural Engineering and Design Management*, vol. 12, no. 5, pp. 333–352, 2016.

[77] W. Shou, J. Wang, X. Wang, and H. Y. Chong, "A comparative review of building information modelling implementation in building and infrastructure industries," *Archives of Computational Methods in Engineering*, vol. 22, no. 2, pp. 291–308, 2015.

[78] B. Fanning, C. M. Clevenger, M. E. Ozbek, and H. Mahmoud, "Implementing BIM on infrastructure: comparison of two bridge construction projects," *Practice Periodical on Structural Design and Construction*, vol. 20, no. 4, article 04014044, 2015.

[79] Y. Ding, "Scientific collaboration and endorsement: network analysis of coauthorship and citation networks," *Journal of Informetrics*, vol. 5, no. 1, pp. 187–203, 2011.

[80] N. J. Van Eck and L. Waltman, "Visualizing bibliometric networks," in *Measuring Scholarly Impact*, pp. 285–320, Springer, Berlin, Germany, 2014.

[81] M. E. J. Newman, "Coauthorship networks and patterns of scientific collaboration," *Proceedings of the National Academy of Sciences*, vol. 101, no. Supplement 1, pp. 5200–5205, 2004.

[82] R. Jin, P. X. Zou, B. Li, P. Piroozfar, and N. Painting, "Comparisons of students' perceptions on BIM practice among Australia. China and UK," *Engineering, Construction and Architectural Management*, 2019.

[83] H.-N. Su and P.-C. Lee, "Mapping knowledge structure by keyword co-occurrence: a first look at journal papers in technology foresight," *Scientometrics*, vol. 85, no. 1, pp. 65–79, 2010.

[84] A. Whyte and J. Donaldson, "Digital model data distribution in civil engineering contracts," *Built Environment Project and Asset Management*, vol. 5, no. 3, pp. 248–260, 2015.

[85] S. Zhang, J. Teizer, J.-K. Lee, C. M. Eastman, and M. Venugopal, "Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules," *Automation in Construction*, vol. 29, pp. 183–195, 2013.

[86] X. Xiong, A. Adan, B. Akinci, and D. Huber, "Automatic creation of semantically rich 3D building models from laser scanner data," *Automation in Construction*, vol. 31, pp. 325–337, 2013.

[87] V. Singh, N. Gu, and X. Wang, "A theoretical framework of a BIM-based multi-disciplinary collaboration platform," *Automation in Construction*, vol. 20, no. 2, pp. 134–144, 2011.

[88] G. Lee, R. Sacks, and C. M. Eastman, "Specifying parametric building object behavior (BOB) for a building information modeling system," *Automation in Construction*, vol. 15, no. 6, pp. 758–776, 2006.

[89] V. Pătrăucean, I. Armeni, M. Nahangi, J. Yeung, I. Brilakis, and C. Haas, "State of research in automatic as-built modelling," *Advanced Engineering Informatics*, vol. 29, no. 2, pp. 162–171, 2015.

[90] U. Isikdag, J. Underwood, and G. Aouad, "An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes," *Advanced Engineering Informatics*, vol. 22, no. 4, pp. 504–519, 2008.

[91] W. Yan, C. Culp, and R. Graf, "Integrating BIM and gaming for real-time interactive architectural visualization," *Automation in Construction*, vol. 20, no. 4, pp. 446–458, 2011.

[92] L. Chen and H. Luo, "A BIM-based construction quality management model and its applications," *Automation in Construction*, vol. 46, pp. 64–73, 2014.

[93] Y.-S. Jeong, C. M. Eastman, R. Sacks, and I. Kaner, "Benchmark tests for BIM data exchanges of precast concrete," *Automation in Construction*, vol. 18, no. 4, pp. 469–484, 2009.

[94] J. Steel, R. Drogemuller, and B. Toth, "Model interoperability in building information modelling," *Software & Systems Modeling*, vol. 11, no. 1, pp. 99–109, 2012.

[95] M. Venugopal, C. M. Eastman, R. Sacks, and J. Teizer, "Semantics of model views for information exchanges using the industry foundation class schema," *Advanced Engineering Informatics*, vol. 26, no. 2, pp. 411–428, 2012.

[96] M. Murphy, E. McGovern, and S. Pavia, "Historic building information modelling (HBIM)," *Structural Survey*, vol. 27, no. 4, pp. 311–327, 2009.

[97] Y. Arayici, "Towards building information modelling for existing structures," *Structural Survey*, vol. 26, no. 3, pp. 210–222, 2008.

[98] M. Golparvar-Fard, F. Peña-Mora, and S. Savarese, "Automated progress monitoring using unordered daily construction photographs and IFC-based building information models," *Journal of Computing in Civil Engineering*, vol. 29, article 04014025, 2015.

[99] Z. Pučko, N. Šuman, and D. Rebolj, "Automated continuous construction progress monitoring using multiple workplace real time 3D scans," *Advanced Engineering Informatics*, vol. 38, pp. 27–40, 2018.

[100] M.-M. Sharif, M. Nahangi, C. Haas, and J. West, "Automated model-based finding of 3D objects in cluttered construction point cloud models," *Computer-Aided Civil and Infrastructure Engineering*, vol. 32, no. 11, pp. 893–908, 2017.

[101] M. Arashpour, A. Heidarpour, A. Akbar Nezhad, Z. Hosseinifard, N. Chileshe, and R. Hosseini, "Performance-based control of variability and tolerance in off-site manufacture and assembly: optimization of penalty on poor production quality," *Construction Management and Economics*, pp. 1–13, 2019.

[102] Y. Wang, Z. Yuan, and C. Sun, "Research on assembly sequence planning and optimization of precast concrete buildings," *Journal of Civil Engineering and Management*, vol. 24, no. 2, pp. 106–115, 2018.

[103] A. Garbers, F. Esmanioto, N. Huber, E. R. Loures, and O. Canciglieri, "Data interoperability assessment though IFC for BIM in structural design—a five-year gap analysis," *Journal of Civil Engineering and Management*, vol. 23, no. 7, pp. 943–954, 2017.

[104] F. Xue, W. Lu, and K. Chen, "Automatic generation of semantically rich as-built building information models using 2D images: a derivative-free optimization approach," *Computer-Aided Civil and Infrastructure Engineering*, vol. 33, no. 11, pp. 926–942, 2018.

[105] J. Jung, S. Hong, S. Yoon, J. Kim, and J. Heo, "Automated 3D wireframe modeling of indoor structures from point clouds using constrained least-squares adjustment for as- built BIM," *Journal of Computing in Civil Engineering*, vol. 30, article 04015074, 2016.

[106] Q. Wang, H. Sohn, and J. C. P. Cheng, "Automatic as-built BIM creation of precast concrete bridge deck panels using laser scan data," *Journal of Computing in Civil Engineering*, vol. 32, article 04018011, 2018.

[107] H.-Y. Lee and I. T. Yang, "Developing as-built BIM model process management system for general contractors: a case study," *Journal of Civil Engineering and Management*, vol. 22, no. 5, pp. 608–621, 2016.

[108] M. Theiler and K. Smarsly, "IFC monitor—an IFC schema extension for modeling structural health monitoring systems," *Advanced Engineering Informatics*, vol. 37, pp. 54–65, 2018.

[109] J. M. D. Delgado, L. J. Butler, I. Brilakis, M. Z. E. B. Elshafie, and C. R. Middleton, "Structural performance monitoring using a dynamic data-driven BIM environment," *Journal of Computing in Civil Engineering*, vol. 32, article 04018009, 2018.

[110] V. Petrovic, M. Yeager, and F. Kuester, "Terrestrial laser scanning for the comprehensive structural health assessment of the baptistery di san giovanni in florence. Italy: an integrative methodology for repeatable data acquisition. visualization and analysis auhess. michael," *Structure and Infrastructure Engineering*, vol. 14, pp. 247–263, 2018.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 1392684, 19 pages
https://doi.org/10.1155/2019/1392684

Research Article

BIM Use by Architecture, Engineering, and Construction (AEC) Industry in Educational Facility Projects

Cristina Moreno,[1] Svetlana Olbina ,[2] and Raja R. Issa[1]

[1]*Rinker School of Construction Management, University of Florida, Gainesville, FL, USA*
[2]*Department of Construction Management, Colorado State University, Fort Collins, CO, USA*

Correspondence should be addressed to Svetlana Olbina; svetlanaolbina@gmail.com

Received 30 January 2019; Revised 15 April 2019; Accepted 9 June 2019; Published 3 July 2019

Guest Editor: Tatjana Vilutiene

In recent years, many public and private sector owners have started to require a building information modeling (BIM) component in new construction projects. Although there has been a significant increase in industry-wide acceptance of BIM, it is still not a standard practice in the educational facility sector. This research aimed at exploring the use of BIM in educational facility projects by the architecture, engineering, and construction (AEC) disciplines. A survey that investigated BIM adoption at the company level, BIM implementation in projects, benefits of using BIM, and obstacles to using BIM was distributed to architects, site engineers, structural engineers, mechanical engineers, and contractors across the United States. The survey results showed that a majority of the respondents from all five disciplines used BIM. BIM was most commonly used for 3D visualization, automation of documentation, and clash detection. The most important benefits of BIM included better marketing and clearer understanding of projects which is crucial for clients such as school students, teachers, and principals. Lack of expertise and need for training seemed to be main obstacles to BIM use. The research contributes to the body of knowledge by showing prevalence of BIM use on educational facility projects and indicating how BIM could help improve collaborative knowledge sharing among designers, contractors, and clients, resulting in better quality educational buildings. These research findings can be used to assist AEC companies that are interested in implementing BIM in the educational facility projects.

1. Introduction

In the past years, building information modeling (BIM) has strongly impacted the architecture, engineering, and construction (AEC) industry as one of the top information and communication technologies used by the industry [1, 2].

The AEC industry uses BIM for 3D visualization, clash detection, feasibility analysis, constructability review, quantity take-off and cost estimate, 4D/scheduling, environmental/LEED analysis, creating shop drawings, and facility management [3–6]. BIM use has potential to improve construction efficiency, enhance collaboration and knowledge sharing among the team members, and support construction-related tasks [7, 8]. Using BIM throughout a project reduces risks by promoting efficiency, by minimizing errors or misinterpretations between designers, engineers, and contractors, and by requiring collaboration and knowledge sharing between all parties involved to ensure accuracy and reliability [9].

In integrated project delivery (IPD), the owner, design team, construction, and operation and maintenance professionals are involved in making decisions in all project phases starting with project programming/pre-design and ending with the operation and maintenance phase. However, in a typical office building, the owner and client are not necessarily the same entity and, thus, clients might be excluded from the design and construction process. On the contrary, in the case of educational buildings, it is important to include the client (e.g., students, teachers, principals, and superintendent) in the process of design, construction, and maintenance of the buildings in order to achieve a high-quality project that would meet the client needs [10]. Previous studies also showed the IPD creates a project environment that allows full utilization of the BIM process; as a result, the client involved in IPD can also benefit from the use of BIM on an educational project [11].

For example, BIM can be used for 3D visual communication, which is much more user-friendly in the case of, e.g., elementary school students as compared to verbal communication. During the design phase, school students can be involved in making decisions about building design by utilizing 3D walkthroughs of a school [12–14]. In addition, BIM can help in the design phase with simulating evacuation of the school occupants in the case of emergency situation (e.g., fire) [15, 16]. Students could also be involved in daylight analysis of a school project with the use of 3D BIM tools; it is important that students evaluate daylighting design as daylight is found to be very beneficial for student well-being and their learning of the course material [16–18]. Another example is the use of BIM for monitoring building energy performance [19, 20]; this process can be incorporated in a high-school curriculum (e.g., physics course) where students could utilize their school building as a living laboratory.

Regardless of all the advancements and potential applications and benefits, BIM is yet to be adopted as the industry-wide standard in the US [21, 22]. Lu et al. conducted a comprehensive review of literature published from 1998 to 2012 and showed that a rigorous research on information and communication technology applications in the AEC industry is missing [1]. Previous research pointed out the need for more research on BIM adoption in general [3] as well as for more specific research focusing on all AEC disciplines [23]. In addition, Son et al. [24] indicated that very little research had been conducted about the attitudes of architects towards BIM adoption. Lee et al. [3] also suggested additional research about correlation between BIM use and factors that affect that use.

Miettinen and Paavola [25] emphasized the need for detailed research on developing specific BIM uses in different project phases by different disciplines. Universities in the USA as facility owners have been using BIM mostly for facility management in the operation and maintenance (O&M) phase of the building life cycle [26–29], while BIM use for design, new construction, and remodeling/renovation of existing educational buildings has been limited [30, 31].

In summary, the literature review indicated a scarcity of literature on BIM use for K-12 (kindergarten to 12th grade) educational facility projects. It also showed that there is limited knowledge regarding the existing use of BIM within the educational facility sector of the AEC industry market. This lack of research on BIM use in educational facility projects was our motivation to conduct this study.

In addition, note that the research presented in this paper was part of a larger study that had a goal to investigate existing use of BIM for educational facilities in the USA and, based on these results, develop guidelines for integrating BIM in this kind of projects. The guidelines were proposed to be used by Florida Department of Education for design and construction of educational facilities. The motivation for this research came from a few examples of BIM standards developed to be used by universities in the USA such as the Ohio State University [32], Indiana University [33], University of Illinois [34], Western Michigan University [35], University of Southern California [36], and Virginia Commonwealth University [37].

Previous studies found that the BIM is beneficial for the entire vertical construction sector (i.e., buildings), and our study had a goal to investigate how BIM could benefit specifically educational facility projects as a subset of the vertical construction projects. To address the above-mentioned research needs, we performed a comprehensive, nationwide assessment of the existing use of BIM on educational facilities in the USA (including both K-12 and university buildings) in different life-cycle phases of projects. The goal of this research was to investigate BIM adoption and use by AEC disciplines in order to obtain a better understanding of their attitudes towards BIM use in educational facility projects. The research objectives were to determine each discipline's perceptions about BIM adoption within their companies, BIM implementation in projects, benefits of using BIM, and obstacles that impede BIM implementation in educational facility projects. More specifically, this research aimed at answering the following questions:

(i) How prevalent is BIM use in educational facility projects?

(ii) What are the BIM applications on educational facility projects?

(iii) How has BIM been used for collaborative knowledge sharing by different stakeholders on educational facility projects?

(iv) How does BIM use help designers address a lack of an efficient method to explore and evaluate different designs of educational facilities and the issues of incomplete, inaccurate, and inconsistent drawings?

(v) How does BIM use help contractors address the issues of large numbers of building system clashes and working with incomplete construction documents which increases the number of RFIs and change orders in educational facilities construction?

(vi) How could BIM help delivering better quality educational facilities for a client?

(vii) How BIM use differs on educational facility projects as compared to other buildings (e.g., commercial buildings)?

2. Literature Review

The literature review presented in this section focuses on all building types as the literature on BIM use on specifically educational facilities was very limited.

BIM as a term is used to present both a building information model and a collaborative methodology used by different project stakeholders. The National Institute of Building Sciences (NIBS) [38] has defined building information *models* as "a digital representation of physical and functional characteristics of a facility . . . [that] serves as a shared knowledge resource for information about a facility." BIM interprets and communicates the attributes of each building system simultaneously through a shared data-rich model that aids all parties involved in the project. This automated model provides easier transfer of data, interference checking, documentation, and exchange of ideas between different disciplines [39]. In addition, building information *modeling* is defined as a collaborative methodology that generates data to be used during the different phases of a building's life cycle such as design, construction, operation, and maintenance [38].

BIM adoption has been on a steady increase since 2007 [40]. In 2007, 28% of the industry adopted BIM, almost half (49%) in 2009 and 71% in 2012. In 2012, 70% of architects, 67% of engineers, and 74% of contractors were implementing BIM. Another McGraw Hill Construction [41] survey of contractors around the world reported that half of the contractors in the USA and Canada have been using BIM for 3–5 years and 8% for over 11 years. The demand for BIM from public and private owners has also been a factor that has encouraged these fast adoption rates amongst design and construction companies. In 2014, one-fourth of the owners in the USA required use of BIM while 43% encouraged but did not require BIM use [42]. Several government entities, like the US General Services Administration (GSA), have required implementation of BIM on all new projects [43].

2.1. Benefits of BIM Implementation in Projects. BIM implementation in projects is affected by willingness of project manager, field engineer, and architect to use BIM, owner's request to use BIM, and complexity of project [22]. Project size and project type [44] as well as the project delivery method and establishing collaborative work environments have significant influence on the BIM implementation in projects [45].

According to Ahn et al. [7], Gheisari and Irizarry [4], and Wang et al. [5], BIM can be implemented in the various phases of a project life cycle (planning, design, construction, operation, and demolition). Thus, the product of BIM is a digital model that provides information about, for example, the design (3D), schedule (4D), cost (5D), and lifecycle analysis (6D) [5, 46]. Gu and London [23] showed that BIM does not have to be utilized in all the project phases and activities. The level of BIM implementation on a project can vary from a complex multidisciplinary BIM use in an online collaborative environment through all project life-cycle phases to simple individual/standalone and discipline-/phase-specific building information models [23]. For example, Cao et al. [44] found that in China, almost one-third of the projects used BIM in only one project phase.

In general, use of BIM creates time and cost benefits [7, 45, 47] resulting from increased efficiency, clearer communication of information, collective efforts [6, 25, 48, 49], more accurate design estimates, and reduced number of design changes [6, 48]. More than half (58%) of the companies indicated that the biggest reward of using BIM was a significant reduction of costs due to resolving conflicts while almost half (48%) reported that the main benefit was improved project quality resulting from lower project risk and better predictability of project outcomes [50].

BIM improves decision-making, safety of construction workers, and operation and maintenance of facilities as well as decreases the number of change orders, number of claims and litigations, and uncertainty [7, 51]. Using BIM on projects means encouraging a collaborative effort from all participants and sharing of ideas and information in a more effective and organized manner than in the traditional approach [7, 25, 45, 52]. Moreover, BIM improves project task quality [44], provides better quality product [6–8, 25, 52], creates possibility of sharing information [49, 52], and improves work efficiency [6, 8, 25, 52].

BIM also helps improve project productivity. Chelson [53] showed that BIM-enabled projects benefitted from field productivity improvement ranging from 5 to 40%. He proposed using the four key indicators of increased productivity such as reduced number of RFI, reduced rework, schedule compliance, and decreased change orders due to plan conflicts. He found that the overall benefit of BIM use is a net savings for the owner ranging from a few percent for competitive bid projects to over 10% for integrated projects. BIM-based projects have 10% of the RFI that a typical non-BIM project would have, leading to an average savings of 9% in management time for a contractor. Trade contractors experience 9% savings of project costs on BIM-enabled projects due to reduced rework and idle time due to site conflicts savings. In addition, Poirier et al. [54] found an increase in labor productivity ranging from 75% to 240% on BIM-enabled projects. In another study, reduced number of change orders led to a savings of 42% of standard costs, RFIs decreased 50% per tool or assembly, and decreased project duration resulted in a savings of 67% as compared to the standard duration [55]. Nath et al. [56] investigated productivity improvement of project activities in terms of total time and processing time. Quantity take-off activity had the largest productivity gain, that is, 72% for processing time and 64% for total time. An overall productivity improvement was about 36% for processing time and 38% for total time.

2.1.1. BIM Benefits to Designers. Over 40% of the professionals from all three AEC industry sectors stated that the value of BIM was crucial during the design development and construction documentation phase [50]. Architects and engineers use BIM to evaluate design options and automatically generate accurate 2D drawings from the 3D model [57]. BIM helps transfer information quickly between different design disciplines [57], and, thus, BIM use enhances their collaboration [8]. Architects also use BIM for 3D visualization and communication with owners [44, 51]. BIM helps architects minimize errors and omissions in documents, reduce rework, and decrease design time [43]. With the incorporation of BIM, architects can automate the development of construction documents, like fabrication details and shop drawings that are easily generated for many building systems from the working model. This automation of construction documents allows architects and engineers to spend more time on the design of the project rather than producing and modifying contract documents while also providing higher accuracy of drawings and diminished risk [9, 46]. Individual capabilities and production are optimized by the software because the system allows for faster modeling and simultaneous manipulation of data; one person using BIM can produce more than three people using CAD [9].

In addition, building information models provide opportunity to perform code compliance review [39], cost estimates, and sustainability analysis in the early design stages [6, 8]. A survey conducted by Bynum et al. [57] indicated that the general perception of the AEC industry is that BIM is ideal for sustainable design because it fosters collaboration between parties. BIM tools enable designers to assess the performance of each building component, the efficiency of sustainable design approaches, and their environmental impact as well [57, 58]. Engineers use BIM to determine structural loads or the requirements for the design. Features of BIM-like automated assembly and digital production are used by engineers to process manufacturing information and coordinate the sequence of different systems with fabricators and subcontractors [39].

2.1.2. BIM Benefits to Contractors. Contractors use building information models to coordinate building systems, detect clashes, and immediately communicate these problems with the parties responsible for the errors [7, 39, 44]. This analysis increases cost and time savings in the construction phase due to discovering design errors in the project and eliminating clashes early on in the project, that is, before any construction starts [39, 59, 60]. Contractors also use BIM for calculating quantity takeoffs and estimating costs for bidding purposes, and planning out project schedules [39, 51] as well as for field management [7]. BIM also improves planning and scheduling of subcontractors. According to contractors, the top two benefits of BIM use in construction were reducing rework and marketing to owners [61]. Therefore, contractors also actively use BIM for visualization and marketing purposes [7].

BIM can be also beneficial for accessing building information models and requests for information (RFIs) on construction site, for solving any construction problems on-site as soon as they arise [7], and for visualizing the sequence of construction activities, which is particularly useful in the case of complex projects [8]. BIM is beneficial for creating a database of information that is generated on a construction site during the construction phase of the project [49]. Another benefit of BIM is that it facilitates prefabrication of the building components off-site, which again reduces the cost and duration of a project [7, 8]. Furthermore, BIM technology is being enabled on construction sites with the use of mobile devices, such as iPads and other handheld tablets. Using mobile devices, the on-site crew can generate, navigate, modify, access, and check the building information model and its attributes operating in real time. This sophisticated imaging technology can also augment on-site training and significantly impacts the way parties, including subcontractors and owners, communicate with each other [62].

2.1.3. BIM Benefits to Owners. Implementing BIM provides a competitive advantage to AEC companies by enabling them to offer new services to owners and guaranteeing owners maximum return on their investment. Public owners have noticed that BIM-based projects are yielding higher quality products and more efficient buildings that result in reduced lifecycle costs [55, 59]. BIM also increases owner engagement by providing clearer and more accurate visualizations of design [63]. This simplifies the communication with owners because realistic 3D visualization models are easier to comprehend than 2D drawings [39].

2.2. Obstacles to BIM Use. Despite all the benefits of BIM use, BIM adoption has been slow [21, 25]. The fragmented nature of the AEC industry inhibits successful adoption of BIM [23, 25]. More specifically, the lack of BIM adoption worldwide could be a result of both nontechnical factors (e.g., interoperability, investment, and training) and organizational factors (e.g., professional liability, intellectual property, and trust). In addition, several interorganizational issues such as reluctance to openly share information, lack of collaboration management tools, security risk, and problems with managing BIM master model could hinder BIM adoption [22, 51]. Moreover, lack of BIM implementation plan, need for cultural change within organization in order to adopt BIM, organizational challenges, increased risk with the use of BIM, and complexity of developing building information model are the barriers to BIM adoption [7, 51]. According to Dodge Data & Analytics' survey [47], the largest obstacles to BIM success were low level of team interest in support for BIM and low level of collaboration among team members.

Several researchers pointed out that the lack of data interoperability among different BIM applications and the lack of software integration impede adoption of BIM [4, 25, 44, 45, 51]. Lack of interoperability can result in inaccurate building information models, thus potentially leading to legal disputes [45].

Additional obstacles to BIM adoption include lack of appropriate legal environment and contracts related to BIM-based project delivery [45] as well as perceived legal matters regarding lack of clarity when determining ownership of the intellectual property and liability for design [3, 7, 8]. From a legal perspective, when all the parties are involved in a close collaboration, it is inevitable that risks and responsibilities overlap or shift from one party to another [64]. To prevent confusion and disputes, the contract should specify the duties and responsibilities of each party involved in order to clarify who faces consequences of any liable errors, inaccuracies, or discrepancies in the model [3, 23, 45].

Another major obstacle to BIM use is that the industry lacks a standard way to evaluate the quality and sustainability of a facility [22] and to assess or collect data related to the benefits of BIM [3]. It is hard to measure the impact of BIM or any other variable for a specific project because no two projects are identical and many other uncontrollable factors influence the results [25, 59]. The industry is in critical need of a standard but it is having difficulty collecting performance metrics or finding a consistent way to analyse and show the direct and indirect benefits of BIM implementation [65].

Moreover, the adoption of BIM carries an initial financial burden that causes companies to be resistant to the use of BIM because of the costs associated with buying the software and training employees [3, 4, 7, 22, 24, 51, 52]. Apart from technical issues, human factors are a critical setback for BIM. The lack of BIM-knowledgeable workers within the design and construction fields presents an obstacle to the implementation of BIM [1, 4, 7, 22, 51, 52]. Personnel who lack proper formal BIM training hinder the project success and the overall collaboration [1, 3, 4, 7, 9, 23]. The level of BIM experience from one design team member to another is uneven, and this additionally limits the potential of BIM [9]. A crucial element for successful BIM use is the level of involvement of all the key disciplines that participate in the project. If not all parties have adopted BIM use as their standard practice, then the resulting model may only have certain systems accounted for. For example, Won et al. [22] and Ahn et al. [7] indicated that lack of subcontractors that can use BIM presents a barrier to BIM adoption. An additional challenge to BIM adoption is worker resistance to new technologies and changes in traditional procedures [7, 23]. This resistance to change prevents the full adoption of BIM within company practices [1, 4, 9, 23]. Also, lack of familiarity with BIM adoption process hinders BIM utilization [3].

3. Research Methods

The goal of the study was to obtain an understanding of BIM use by designers and contractors in educational facility projects. In order to achieve this goal, a survey instrument was developed based on a literature review. The survey had a total of 32 questions on various topics concerning participant perceptions on BIM use on educational facility projects (see Appendix A). These questions were grouped in the following major sections: demographics, BIM adoption at the company level, BIM implementation at the project level, perceived benefits of BIM use, and perceived obstacles to BIM use. Based on the Institutional Review Board- (IRB-) approved survey protocol, participants were asked to consent to participate in the survey prior to commencing. Participants were informed that they were required to have experience with educational facility projects when they were asked to voluntarily agree to participate in the survey and also as part of the survey itself. Each participant was given two weeks from the initial moment of contact to consent to participate.

The survey was developed using SurveyMonkey, and the link to the survey was emailed to architects, engineers, and contractors that were the members of professional AEC societies in the USA including the American Institute of Architects (AIA), Associated Builders and Contractors (ABC), the Associated General Contractors of America (AGC), and the American Society of Civil Engineers (ASCE). A total of 1,265 participants were reached via email; 569 from architecture firms, 344 from engineering firms, and 352 from construction companies.

Eighty-eight responses to the survey were received from the architects, engineers (site, structural, and MEP), and contractors. Only the responses from 68 participants that responded to the survey question about whether or not they used BIM were included in the analysis. Responses of 53 respondents that stated they had an experience with using BIM on educational facility projects were included in the analysis of the questions related to BIM adoption at the company level and BIM implementation at the project level. However, responses of all the survey respondents (68) to the questions related to perceived benefits of BIM and obstacles to BIM implementation were included in the analysis. The survey responses were analysed using descriptive statistics. The cross-tabulation method was used to analyse responses according to the respondent's role in the design and construction process in order to determine findings by discipline. Note that, in this paper, "N" refers to the number of respondents, while "n" refers to the number of selections made in the case of "select all that apply" type of questions.

4. Results and Discussion

The five roles used to analyse the survey responses included architect, site engineer, structural engineer, MEP engineer, and contractor. About half of the 88 respondents (47, 53%) were architects, while 15 (17%) were contractors. Almost one-third of the respondents (26, 30%) were engineers comprising site engineers (7, 8%), structural engineers (14, 16%), and MEP engineers (5, 6%) (Figure 1).

4.1. BIM Adoption at the Company Level. The respondents were asked a series of questions regarding the BIM adoption in their companies. More than three-fourths (53, 78%) of the responding professionals used BIM. Regarding specific disciplines, majority of the mechanical engineers, structural

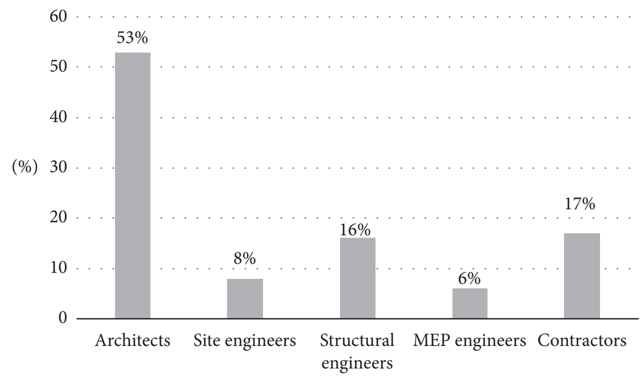


Figure 1: Distribution of the survey participants by the discipline (total $N = 88$).

engineers, architects, site engineers, and contractors claimed to use BIM in their practice (Figure 2).

When asked about the driving forces for BIM implementation in educational facility projects within their company, a majority of the architects thought that management was the main driving force, while a minority stated that the clients and competition from other companies were driving BIM implementation (Table 1). However, the majority of the structural engineers, MEP engineers, and contractors perceived clients to be the main reason for implementing BIM. This is a very important finding because it shows that owners/clients of educational facilities might be encouraging or requesting use of BIM as it most likely helps them better visualize and understand a project. All of the site engineers perceived the pressure of competing with other companies to be a driving force. Note that the respondents were asked to "select all that apply" when answering this question.

Since one of the measures of the extent of BIM adoption is the number of BIM-knowledgeable employees within a company, the average percent of BIM-knowledgeable employees within each of the five participating disciplines was calculated (Figure 3). The MEP engineers had the highest average percent of BIM-knowledgeable employees within their companies, followed by the site engineers and architects.

When asked about the business value of using BIM that their companies realized, the largest proportion of the architects along with all of the site engineers stated that their companies were just starting to see the potential value of using BIM (Table 2). The majority of the contractors and structural engineers claimed to have optimized the value of BIM use in their current use. Minority of the structural engineers and contractors perceived that their companies were just starting to see the potential value of BIM use.

The survey participants were asked about the current methods that their companies employed to encourage the use of BIM. The largest proportion of the responding architects said that their companies required the use of BIM, and more than a third of the architects claimed that their companies provided BIM training (Table 3). All the responding site engineers indicated that their companies compensated employees for continuing education as the way to encourage BIM use. The majority of the responding structural engineers and almost half of the contractors answered that their companies provide BIM training to encourage the use of BIM.

When asked about their perceptions about the best ways to provide BIM expertise, a majority of the respondents from all five disciplines suggested either providing internal training or hiring new BIM-skilled professionals (Table 4). All the responding site engineers thought that hiring new skilled BIM professionals was the best way to acquire BIM expertise for the company, while majority of the MEP engineers, structural engineers, and contractors and the largest proportion of the architects thought that internal training was the best way to acquire BIM expertise.

The respondents who claimed that their companies did not use BIM (15, 22%) were further asked about the reasons for their company's lack of BIM involvement (Table 5). The only discipline that responded that their company used BIM in the past but no longer uses it was the site engineers. None of the respondents claimed to have never heard of BIM. Surprisingly, the only disciplines that responded that their company had no interest in using BIM were the architects and contractors. However, majority of the responding contractors, structural engineers, and site engineers that did not use BIM stated that these companies were interested in implementing BIM.

4.2. BIM Implementation on Educational Facility Projects. Regarding BIM implementation on projects, the survey participants were asked to estimate the percent of educational facility projects in which certain BIM applications had been used in the previous five years (Table 6). The average percent of all the responses was calculated for each application and cross tabulated with the role of the respondents to determine the existing use of BIM applications by different disciplines in different phases of the project.

All the responding disciplines indicated that BIM was used most frequently in the design phase of educational facility projects. The architects and contractors used BIM for 3D visualization and automation of documentation as well as for clash detection in the majority of the projects. Similarly, the site engineers claimed to use BIM for 3D visualization and structural analysis in almost all of their

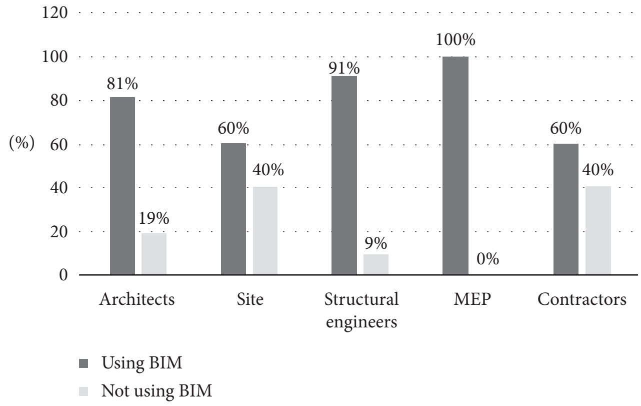


Figure 2: Relationship between the role of the respondent and the company's use of BIM (total $N = 68$).

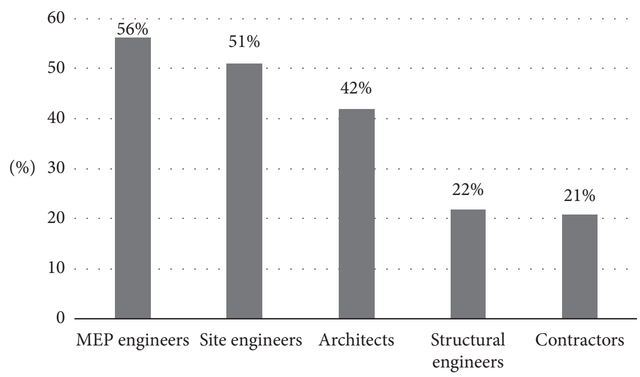


Figure 3: BIM-knowledgeable employees within disciplines ($N = 52$).

Table 1: Relationship between the role of the respondent and the perceived driving force for BIM implementation in educational facility projects*.

Perceived BIM implementation drivers	Architects $N_A = 25$ $n_A = 49$	Site engineers $N_{SE} = 3$ $n_{SE} = 6$	Structural engineers $N_{STE} = 10$ $n_{STE} = 19$	MEP engineers $N_{MEPE} = 5$ $n_{MEPE} = 9$	Contractors $N_C = 9$ $n_C = 19$
Clients	11 (44%)	0 (0%)	9 (90%)	4 (80%)	9 (100%)
Subcontractors	1 (4%)	1 (33%)	1 (10%)	0 (0%)	0 (0%)
Management	13 (52%)	1 (33%)	2 (20%)	1 (20%)	3 (33%)
Manufacturers/fabricators	2 (8%)	1 (33%)	1 (10%)	0 (0%)	0 (0%)
Government permitting agencies	3 (12%)	0 (0%)	2 (20%)	0 (0%)	0 (0%)
Competition from other companies	10 (40%)	3 (100%)	4 (40%)	2 (40%)	6 (66.6%)
Other	9 (36%)	0 (0%)	0 (0%)	2 (40%)	1 (11.1%)

Note. *Select all that apply. Percent (%) = number of selections divided by number of respondents for a specific discipline. Total $N = 52$ and total $n = 102$.

Table 2: Relationship between the role of the respondent and their company's perceived current business value of using BIM.

Perceived business value of using BIM	Architects $N_A = 25$ (48.1%)	Site engineers $N_{SE} = 3$ (5.8%)	Structural engineers $N_{STE} = 10$ (19.2%)	MEP engineers $N_{MEPE} = 5$ (9.6%)	Contractors $N_C = 9$ (17%)
We have optimized the value of BIM in our current use	9 (36%)	0 (0%)	5 (50%)	2 (40%)	7 (78%)
We are just starting to see the potential value of using BIM	10 (40%)	3 (100%)	4 (40%)	1 (20%)	2 (22%)
We are getting no meaningful value from BIM	6 (24%)	0 (0%)	1 (10%)	2 (40%)	0 (0%)

Note. Total $N = 52$.

Table 3: Relationship between the role of the respondent and their company's method for encouraging BIM use.

Methods companies use to encourage the use of BIM	Architects $N_A = 25$ (48%)	Site engineers $N_{SE} = 3$ (6%)	Structural engineers $N_{STE} = 10$ (19%)	MEP engineers $N_{MEPE} = 5$ (10%)	Contractors $N_C = 9$ (17%)
It does not encourage use of BIM	2 (8%)	0 (0%)	1 (10%)	1 (20%)	1 (11.1%)
It provides training	9 (36%)	0 (0%)	6 (60%)	2 (40%)	4 (44.4%)
It requires it	10 (40%)	0 (0%)	3 (30%)	2 (40%)	3 (33.3%)
It compensates employees for their continuing education	0 (0%)	3 (100%)	0 (0%)	0 (0%)	1 (11.1%)
Other	4 (16%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

Note. Total $N = 52$.

Table 4: Relationship between the role of the respondent and the best method for acquiring BIM expertise.

The best method for acquiring BIM expertise	Architects $N_A = 25$ (48%)	Site engineers $N_{SE} = 3$ (6%)	Structural engineers $N_{STE} = 10$ (19%)	MEP engineers $N_{MEPE} = 5$ (10%)	Contractors $N_C = 9$ (17%)
Hire new BIM-skilled professionals	8 (32%)	3 (100%)	3 (30%)	0 (0%)	3 (33.3%)
Internal training	12 (48%)	0 (0%)	6 (60%)	5 (100%)	5 (55.6%)
Online seminar	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Outside training	2 (8%)	0 (0%)	0 (0%)	0 (0%)	1 (11.1%)
Other	2 (8%)	0 (0%)	1 (10%)	0 (0%)	0 (0%)

Note. Total $N = 52$.

Table 5: Relationship between role of the respondent and the reason for their company's lack of BIM involvement.

Reasons for lack of BIM involvement	Architects $N_A = 6$ (40%)	Site engineers $N_{SE} = 2$ (13%)	Structural engineers $N_{STE} = 1$ (7%)	MEP engineers $N_{MEPE} = 0$ (0%)	Contractors $N_C = 6$ (40%)
My company does not use BIM but would like to implement BIM	1 (17%)	1 (50%)	1 (100%)	0 (0%)	3 (50%)
My company has used BIM in the past but no longer uses it	0 (0%)	1 (50%)	0 (0%)	0 (0%)	0 (0%)
My company outsources BIM	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (33.3%)
My company has no interest in using BIM	5 (83%)	0 (0%)	0 (0%)	0 (0%)	1 (16.7%)
I have never heard of BIM	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

Note. Total $N = 15$.

Table 6: Relationship between the role of the respondent and the average percentage of educational facility projects in which they have used the specific BIM applications in the previous five years by the project phase.

Building phase	Types of BIM applications used in projects (average % of projects)	Architects $N_A = 22$ (45.8%)	Site engineers $N_{SE} = 3$ (6.3%)	Structural engineers $N_{STE} = 9$ (18.7%)	MEP engineers $N_{MEPE} = 5$ (10.4%)	Contractors $N_C = 9$ (18.7%)
Design phase	Automation of documentation	64%	75%	71%	67%	61%
	3D visualization	69%	92%	66%	51%	67%
	Space planning and validation	44%	33%	34%	67%	15%
	Automated checking of code compliance	6%	20%	3%	0%	3%
	Clash detection and collision assessment	49%	75%	54%	50%	68%
	Structural analysis	44%	93%	69%	50%	39%
	MEP analysis	35%	77%	46%	60%	54%
	Sustainability analysis (LEED)	29%	39%	32%	44%	18%
Construction phase	Geographic information systems (GIS) and site-specific analysis	20%	17%	0%	33%	7%
	4D scheduling and simulation of construction activities	8%	32%	23%	17%	38%
	5D quantity take-off and cost estimate	9%	35%	20%	17%	45%

Table 6: Continued.

Building phase	Types of BIM applications used in projects (average % of projects)	Architects $N_A = 22$ (45.8%)	Site engineers $N_{SE} = 3$ (6.3%)	Structural engineers $N_{STE} = 9$ (18.7%)	MEP engineers $N_{MEPE} = 5$ (10.4%)	Contractors $N_C = 9$ (18.7%)
Operation and maintenance phase	6D facilities management and maintenance	5%	12%	20%	0%	17%
All phases	Building performance analysis	24%	32%	20%	70%	11%
	Lifecycle analysis	15%	20%	10%	31%	12%

Note. Total $N = 48$.

educational projects. Similar to the architects and contractors, the structural engineers indicated that they used BIM for automation of documentation and 3D visualization most often in their projects, and, as expected, for structural analysis. Frequent use of BIM for 3D visualization is an important finding as it indicates a potential of BIM to help clients of educational facilities (e.g., students and teachers) to better understand the project as well as to communicate their ideas and needs to the design team. The MEP engineers used BIM for space planning most frequently in their educational building projects. As expected, during the construction phase of educational projects, BIM was used primarily by contractors and mostly for quantity take-offs and estimating, and scheduling and 4D simulations of construction activities as this is the major scope of their work. All the respondents regardless of their discipline indicated less frequent use of BIM in the operations and maintenance (O&M) phase of the educational facility projects. The reason for this might be that these disciplines are not frequently involved in O&M of the buildings. As expected, the MEP engineers reported that they often used BIM for building performance analysis during the entire life cycle of educational buildings.

The relationship between the role of the respondent and the discipline these respondents primarily share BIM information with when working on the design and construction of educational facility was investigated to understand the level of collaborative knowledge sharing among project stakeholders (Table 7). The architects shared BIM information primarily with engineers and to a lesser extent with the owners of the projects and the contractors. The site engineers stated that they only shared BIM information with the architects. The structural engineers mainly shared BIM information with architects and seldom with other engineers and subcontractors. The MEP engineers only shared BIM information with architects and the owners. The finding that design disciplines collaborate and share information primarily with the architects as the central design discipline was expected because of the scope of design work and the design workflow. However, it was not expected that architects would report less frequent information sharing with contractors, although this might be expected in the case of design-bid-build delivery of the projects. The contractors indicated that they generally shared BIM information with all the other disciplines, mostly with architects, engineers, and owners. As expected, structural engineers and contractors were the only disciplines that shared BIM information with subcontractors. Overall, the survey responses indicated collaboration among the various stakeholders driven by the specific educational facility project phase and scope of the particular work.

When asked about BIM software that their company utilizes, as anticipated, the large majority of the architects responded that they used Revit™ Architecture (Table 8). The site engineers solely used the Revit™ Suite software, which includes Revit™ Architecture, Revit™ Structure, and Revit MEP™. Site engineers was the only discipline that did not use Navisworks™, which is justifiable by the fact that Navisworks™ is mostly used for coordination of buildings systems and clash detection which is out of the site engineer's scope of work. As expected, the structural engineers primarily used Revit™ Structure along with Tekla Structures™ and Navisworks™ because they meet the needs of their scope of work. The MEP engineers used mostly Revit MEP™ and Revit Structure™ followed by Navisworks™. This particular software use by MEP engineers is expected as main purpose of their use of BIM is to model MEP systems and coordinate the systems with the structure of a building. The contractors used almost equally Navisworks™ and Revit Architecture™, Revit MEP™, and Revit Structure™ which again might be explained by the BIM applications needed by the contractors such as constructability review, building system coordination, clash detection, and 4D scheduling of construction activities. In summary, the Autodesk software was the most utilized BIM software by the different disciplines. Fewer respondents used ArchiCAD™, Bentley™, VICO Construction™, Bentley Facilities Management™, and Digital Project™. Note that the respondents were asked to "select all that apply" when answering this question.

4.3. Perceived Benefits of BIM Use in Educational Facility Projects. The respondents were asked to select all the design and construction phases in which they perceived BIM use to be valuable for their company (Table 9). Note that the respondents were asked to "select all that apply" when answering this question. In addition, all the respondents regardless of whether they used BIM or not were asked to answer this question. As anticipated, the architects perceived that BIM implementation was most valuable in the design phases, i.e., in schematic design, design development, and construction documentation phases. Architects found BIM

Table 7: Relationship between the role of the respondent and the disciplines they primarily share BIM information with when working on educational facility projects.

Disciplines respondents share BIM information with	Architects $N_A = 25$ (48%)	Site engineers $N_{SE} = 3$ (6%)	Structural engineers $N_{STE} = 10$ (19%)	MEP engineers $N_{MEPE} = 5$ (10%)	Contractors $N_C = 9$ (17%)
Owner	4 (16%)	0 (0%)	0 (0%)	1 (20%)	2 (22.2%)
Architect	1 (4%)	3 (100%)	8 (80%)	4 (80%)	3 (33.3%)
Engineer	14 (56%)	0 (0%)	1 (10%)	0 (0%)	2 (22.2%)
Contractor	3 (12%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Subcontractor	0 (0%)	0 (0%)	1 (10%)	0 (0%)	1 (11.1%)
Manufacturer	1 (4%)	0 (0%)	0 (0%)	0 (0%)	1 (11.1%)
Other	2 (8%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

Note. Total $N = 52$.

Table 8: Relationship between respondent's role and the BIM software they use in projects*.

BIM software	Architects $N_A = 24$ $n_A = 54$	Site engineers $N_{SE} = 3$ $n_{SE} = 7$	Structural engineers $N_{STE} = 10$ $n_{STE} = 33$	MEP engineers $N_{MEPE} = 5$ $n_{MEPE} = 19$	Contractors $N_C = 9$ $n_C = 41$
Revit Architecture™	22 (91.7%)	3 (100%)	3 (30%)	3 (60%)	8 (88.9%)
Revit Structure™	6 (25%)	3 (100%)	9 (90%)	5 (100%)	6 (66.7%)
Revit MEP™	8 (33.3%)	1 (33.3%)	4 (40%)	5 (100%)	7 (77.8%)
Bentley™	1 (4.2%)	0 (0%)	1 (10%)	0 (0%)	1 (11.1%)
Bentley FM™	0 (0%)	0 (0%)	1 (10%)	0 (0%)	2 (22.2%)
ArchiCAD™	2 (8.3%)	0 (0%)	0 (0%)	0 (0%)	2 (22.2%)
Digital Project™	1 (4.17%)	0 (0%)	1 (10%)	0 (0%)	0 (0%)
Tekla Structure™	0 (0%)	0 (0%)	6 (60%)	0 (0%)	2 (22.2%)
Ecotect™	5 (20.8%)	0 (0%)	1 (10%)	1 (20%)	0 (0%)
VICO Construction™	0 (0%)	0 (0%)	0 (0%)	0 (0%)	3 (33.3%)
Navisworks™	6 (25%)	0 (0%)	6 (60%)	4 (80%)	8 (88.9%)
Other	3 (12.5%)	0 (0%)	1 (10%)	1 (20%)	2 (22.2%)

Note. *Select all that apply. Percent (%) = number of selections divided by number of respondents for a specific discipline. Total $N = 51$ and total $n = 154$.

Table 9: Relationship between the role of the respondent and the perceived value of BIM in different phases of the design and construction process*.

Project phases	Specific project phases	Architects $N_A = 30$ $n_A = 160$	Site engineers $N_{SE} = 4$ $n_{SE} = 15$	Structural engineers $N_{STE} = 11$ $n_{STE} = 44$	MEP engineers $N_{MEPE} = 5$ $n_{MEPE} = 34$	Contractors $N_C = 15$ $n_C = 78$
Design	Predesign	9 (30%)	0 (0%)	1 (9%)	3 (60%)	4 (27%)
	Schematic design	22 (73%)	2 (50%)	5 (45%)	4 (80%)	7 (47%)
	Design development	23 (77%)	3 (75%)	8 (73%)	4 (80%)	10 (67%)
	Construction documentation	23 (77%)	4 (100%)	9 (82%)	4 (80%)	12 (80%)
Construction	Bidding process	14 (47%)	0 (0%)	3 (27%)	3 (60%)	9 (60%)
	Preconstruction	15 (50%)	2 (50%)	4 (36%)	4 (80%)	10 (67%)
	Construction administration	19 (63%)	2 (50%)	6 (55%)	3 (60%)	11 (73%)
	Fabrication	15 (50%)	1 (25%)	7 (64%)	4 (80%)	6 (40%)
	Close-out/commissioning	8 (27%)	0 (0%)	0 (0%)	2 (40%)	5 (33%)
Operation and maintenance	Operation and maintenance	12 (40%)	1 (25%)	1 (9%)	3 (60%)	4 (27%)

Note. *Select all that apply. Percent (%) = number of selections divided by number of respondents for a specific discipline. Total $N = 65$ and total $n = 331$.

least valuable in the closeout phase of educational facility projects, most likely because they are not involved in this project phase. The site engineers and structural engineers perceived BIM to be most valuable in the construction documentation phase. The reason for this might be that these two disciplines are heavily involved in producing construction documents and, therefore, are able to experience BIM benefits in this phase. The MEP engineers was the only discipline that believed that BIM was consistently valuable in all phases of the design and construction process. Majority of MEP engineers found BIM beneficial in operation and maintenance (O&M) of educational facilities; the reason for this might be that MEP engineers are heavily involved in this project phase and, therefore, can benefit from BIM use in O&M. As expected, the contractors found BIM to be most valuable in the construction documentation phase, construction administration phase, and design development and preconstruction phases because these phases directly relate to their scope of work and, thus, they could experience BIM benefits in these phases. In summary, the majority of the responding disciplines found BIM beneficial in the schematic design and design development phases in which client involvement and input is very important for creating a high-quality educational project.

Next, the survey participants were asked to use a 5-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree) to express their agreement with the specific benefits of BIM use for the design and construction of educational facilities. For the analysis of these responses, a mean (that is, average rating score) was calculated for each of the five roles of the respondents, and the benefits were grouped according to the educational facility project phase (Table 10). For further analysis, the means were grouped into a ranking category. In this research, the means between 1.00 and 1.49 were considered as strongly disagree, means between 1.50 and 2.49 were considered as disagree, means between 2.50 and 3.49 were accounted for as neither agree nor disagree, means between 3.50 and 4.49 were considered as agree, and means above 4.50 were considered as strongly agree. Note that all the respondents regardless of whether they used BIM or not were asked to answer this question.

4.3.1. BIM Benefits in the Design Phase of Educational Facility Projects. All the responding professionals regardless of their discipline agreed that the BIM was beneficial for enabling automation of documentation. Architects and site engineers more than other disciplines agreed that BIM was beneficial for evaluating different design alternatives which is expected due to the fact that these two disciplines are focused on design. Use of BIM also allows clients (e.g., students, teachers, school administrators) to be involved in visually evaluating different designs and selecting the one that would best meet their needs. In addition, site engineers and structural engineers were the only two disciplines that agreed that the use of BIM resulted in allowing more time to be spent on design rather than on contract documentation. All the respondents from the design disciplines except the MEP engineers agreed that the BIM was beneficial for lowering project risk because it helped discovering errors, omissions, and conflicts before construction started. According to site engineers, structural engineers, and contractors, BIM provides benefit of faster reviews for approval and permits.

4.3.2. BIM Benefits in the Construction Phase of Educational Facility Projects. Contractors and site and MEP engineers agreed that BIM use is beneficial for reducing RFIs, change orders, and claims. These three disciplines also felt that the use of BIM helped reduce the project delivery time as well as material use and site waste. As expected, contractors was the only discipline that indicated that BIM helped them reduce construction and production costs since they are the primary discipline directly involved in construction and, therefore, could benefit from the BIM use in this phase. Interestingly, only site and MEP engineers indicated that BIM was beneficial for modular construction and prefabrication, while other responding disciplines were neutral regarding these benefits. Typically, a majority of MEP and site components are prefabricated and this might be a reason that these disciplines were perceiving benefits of BIM use for prefabrication. The benefits of BIM for improving construction safety were only recognized by MEP engineers; the other disciplines neither agreed nor disagreed with this BIM benefit.

4.3.3. BIM Benefits in Both Design and Construction Phases of Educational Facility Projects. Structural engineers strongly agreed and the respondents from the remaining four disciplines agreed with the statement that BIM was beneficial for increasing engagement of the educational building client (e.g., students, teachers, principals, and superintendents) and providing the client with clearer visual understanding of the 3D building information model in both design and construction of educational facilities. Respondents from all five disciplines either strongly agreed or agreed that using BIM as a new marketing tool for firms was beneficial as it might help attract clients/users of educational buildings to select their firm for a project. Site engineers and contractors were the two disciplines that agreed that BIM helps with increasing productivity and efficiency. These two disciplines are directly involved in construction of an educational building and, therefore, can experience impact of BIM on efficiency and productivity of construction. Interestingly, site engineers was the only discipline that agreed that BIM helps with sustainability efforts on the educational project. Similarly, site engineers strongly agreed and other disciplines agreed that BIM use encourages use of other information technologies such as Unity and GIS.

4.3.4. BIM Benefits in Both Construction and O&M Phases of Educational Facility Projects. Site engineers, MEP engineers, and contractors agreed that BIM was beneficial for creating accurate as-built models of educational facility. The as-built documentation is an important final project deliverable prepared by contractor and handed over to an owner to be used during the O&M phase of the project. This might be a reason for contractor opinion about this benefit. MEP engineers can be involved in the O&M phase and, thus, could be users of these as-built models and, as a result, experience this BIM benefit.

4.3.5. BIM Benefits in All the Building Phases of Educational Facility Projects. The survey respondents recognized several BIM benefits that applied to all educational project phases. For example, all the respondents except architects agreed that BIM improves collaboration among the disciplines. As expected, contractors, and interestingly, site engineers, agreed that BIM increases

Table 10: Relationship between the role of the respondent and their level of agreement with perceived benefits of using BIM in educational facility projects (mean/average rating score) by the project phase.

Project phase	BIM benefits	Architects $N_A = 30$ (47.6%)	Site engineers $N_{SE} = 4$ (6.3%)	Structural engineers $N_{STE} = 10$ (15.9%)	MEP engineers $N_{MEPE} = 5$ (7.9%)	Contractors $N_C = 14$ (22.2%)
Design phase	Evaluates the impact of different design solutions	3.50	4.00	3.10	3.40	3.43
	Allows more time to be spent on design than on contract documentation	3.03	3.75	3.60	2.80	3.36
	Lowers risk and better predicts outcomes due to discovery of errors, omissions and conflicts prior to construction	3.53	4.00	3.70	3.20	4.00
	Enables automation of documentation (better accuracy and accounts for adjustments and changes automatically)	3.63	4.25	3.60	3.60	4.00
	Enables faster reviews for approvals and permits	2.57	3.75	3.50	2.80	3.79
Construction phase	Reduces RFI's, change orders, claims, and conflicts	3.27	4.00	3.40	3.60	4.07
	Reduces construction and production costs	2.97	3.00	3.30	3.40	4.14
	Reduces project delivery time	3.03	4.00	3.30	3.60	4.00
	Facilitates modular construction	3.13	4.25	3.10	4.00	3.43
	Increase prefabrication	3.07	3.50	3.10	3.60	3.36
	Reduces on-site waste and materials use	2.90	3.75	3.00	4.20	3.50
	Improves construction safety	2.47	3.00	2.80	3.60	3.21
Both design and construction phases	Increases client engagement and provides clearer understanding of 3D visualizations	3.97	4.00	4.60	4.20	4.36
	Increases productivity and efficiency	3.30	3.50	3.40	3.20	4.21
	Encourages consideration for sustainable building systems that conserve energy	3.03	3.75	3.30	2.60	3.36
	Serves as a new marketing tool for firms	3.77	3.75	4.50	4.60	4.36
	Encourages use of other technologies (GIS, unity, etc.)	3.07	4.50	3.20	4.00	3.43
Both construction and O&M phases	Provides more accurate as-built deliverables	3.27	3.75	3.40	3.60	4.07
All project phases	Improves collaboration and communication between disciplines due to more reliable and direct data exchange from a single resource of information	3.43	4.00	4.20	4.00	3.93
	Increases project profitability	2.97	3.75	3.10	2.80	4.07
	Allows for long-term data assessment	3.37	4.50	3.50	3.40	3.29

Note. Total $N = 63$.

project profitability in all the phases of the educational building project. Site engineers and structural engineers were only two disciplines that found BIM was beneficial for the long-term data assessment on educational facility project.

Overall, site engineers was the discipline that agreed with the majority of the listed benefits while architects agreed with only a few BIM benefits offered in the survey instrument.

4.4. Perceived Obstacles to BIM Use in Educational Facility Projects. The survey participants were asked to use a 5-point Likert scale (1 = not likely at all, 2 = somewhat likely, 3 = moderately likely, 4 = very likely, and 5 = extremely likely) to express their opinion about the obstacles that prevent BIM use on educational facility projects. For the analysis of these responses a mean (that is, average rating score) was calculated for each of the five roles of the respondents (Table 11). These means where then grouped into a ranking category as follows. In this research, the resulting means between 1.00 and 1.49 were considered as not likely at all, means between 1.50 and 2.49 were considered as somewhat likely, means between 2.50 and 3.49 were accounted for as moderately likely, means between 3.50 and 4.49 were considered as very likely, and any means above 4.50 were considered as extremely likely. Note that all the respondents regardless of whether they used BIM or not were asked to answer this question.

4.4.1. Cost. The contractors was the only discipline that thought that cost of software and hardware and cost of hiring BIM-savvy professionals were the obstacles that would very likely hinder wider implementation of BIM on educational facility projects. According to the site and structural engineers, lack of quantifiable benefits due to BIM use would very likely prevent BIM use. In addition, the site engineers and contractors indicated that it would be difficult to justify the use of BIM on fast-paced and small educational facility projects.

4.4.2. Demand. All the respondents regardless of the discipline felt that insufficient demand for BIM use by owners would either somewhat likely or moderately likely prevent the BIM use. This finding might indicate the willingness of these professionals to use BIM even if owners do not require it.

4.4.3. BIM Professionals. Regarding the obstacles related to BIM professionals, the site engineers and contractors thought that lack of expertise and need for training as well as unclear roles and responsibilities of the participants in the educational facility projects would very likely prevent BIM use. The architects, structural engineers, and MEP engineers indicated that these obstacles would moderately likely hinder the use of BIM on educational buildings. In addition, MEP engineers and architects were two disciplines that reported the largest number of BIM-savvy professionals in their firms, which might explain why they did not see this as an obstacle.

4.4.4. BIM Process. The site engineers and contractors perceived that disruption in workflow which would happen due to the implementation of new BIM-based processes would very likely hinder BIM implementation on educational facility projects. In addition, the site engineers was the only discipline that thought that lack of software interoperability would very likely obstruct BIM use. On the contrary, none of the disciplines indicated that vulnerability or security of file sharing was likely to prevent BIM implementation on educational facility projects.

4.4.5. Legal Obstacles. When asked about legal-related issues as the potential obstacles to BIM use on educational facility projects, site engineers and contractors stated that the lack of BIM standards would very likely hinder BIM implementation. Respondents from most of the surveyed disciplines felt that lack of precedence, established laws, and regulations about BIM use would moderately likely prevent BIM implementation. Only site engineers indicated that legal liabilities of the BIM process would very likely impede BIM use.

In summary, similar to the BIM benefits, the site engineers was also a discipline that experienced the most obstacles. On the contrary, architects and MEP engineers disagreed or were neutral regarding all the listed obstacles meaning that they did not perceive that these obstacles would prevent them from using BIM in their practice.

The survey participants were also asked whether they had any disputes related to BIM implementation in educational facility projects. Most of the respondents indicated that their companies have not experienced disputes while using BIM (Table 12). Of those respondents that stated that BIM use has led to certain disputes, the most commonly mentioned reason for these disputes was related to liability of system designs. The second reason for disputes was related to intellectual property ownership of the building information model; all disciplines except the MEP engineers specified that this was a problem with BIM use. One architect indicated that their firm had disputes related to adequate compensation for BIM services, while another architect stated that BIM-related disputes happened because other disciplines were not using BIM. One structural engineer indicated that disputes arose due to different levels of model accuracy. Note that the respondents were asked to "select all that apply" when answering this question.

5. Comparison of Current Findings and Previous Research

In order to answer the research question on how BIM use differs on educational facility projects as compared to other projects (e.g., commercial buildings) as well as to identify the contributions of our study, the authors performed the comparison of this research findings and previous research. Please note that our research focused on BIM use in educational facility projects and that there is very limited previous research on this topic. Therefore, we expanded our literature search on BIM use in general, that is, without focusing on a specific building type.

Table 13 shows the comparison of our study and previous research in regard to BIM benefits. The analysis of the results is performed using the data presented in Table 10. If majority of the disciplines in our study either agreed or strongly agreed (that is, mean score was larger than 3.50) with the BIM benefits shown in Table 10, the check mark was assigned to that specific benefit in Table 13. Regarding BIM benefits in the design, construction, and O&M phases, our study confirmed several benefits of using BIM on educational facility project that were very similar to BIM benefits experienced on, e.g., commercial buildings and identified by previous research. There were a few BIM

Table 11: Relationship between the role of the respondent and their perception of the obstacles preventing the use of BIM (mean/average rating score).

Obstacle category	Obstacles that prevent BIM use	Architects $N_A = 30$ (48.4%)	Site engineers $N_{SE} = 4$ (6.5%)	Structural engineers $N_{STE} = 9$ (14.5%)	MEP engineers $N_{MEPE} = 5$ (8.1%)	Contractors $N_C = 14$ (22.6%)
Cost	Cost of software and new hardware to keep up with the software	3.10	2.75	2.67	3.00	4.00
	Cost of hiring experienced staff	3.20	3.25	2.67	2.80	3.93
	Lack of substantial quantifiable benefits and evaluation methods	3.20	3.75	3.56	2.80	3.21
	Fast-paced and small-sized projects do not justify the time needed for the cost of implementing BIM	3.00	3.50	3.11	3.20	3.50
Demand	Not enough owner demand	2.90	3.25	3.30	2.20	3.43
BIM professionals	Lack of expertise and need for training	3.33	3.50	3.33	3.40	3.86
	Unclear responsibilities, assigned roles, and BIM deliverables	3.07	4.25	2.89	3.00	3.69
BIM process	Disruption in workflow to implement new BIM processes	3.21	4.25	3.44	2.40	3.79
	Vulnerability or security of file sharing	2.45	3.25	2.78	2.00	3.29
	Lack of software interoperability	3.10	4.00	3.11	2.80	3.29
Legal issues	Lack of BIM standards	3.03	3.50	3.44	2.40	3.50
	Lack of precedence, established laws, and regulations about BIM use	2.87	3.25	2.78	2.20	3.21
	Legal liabilities of the BIM process	2.97	3.75	3.22	2.40	3.07

Note. Total $N = 62$.

Table 12: Relationship between the role of the respondent and the kind of disputes their companies have encountered when implementing BIM in educational facility projects*.

Types of disputes	Architects $N_A = 25$ $n_A = 26$	Site engineers $N_{SE} = 3$ $n_{SE} = 4$	Structural engineers $N_{STE} = 10$ $n_{STE} = 12$	MEP engineers $N_{MEPE} = 5$ $n_{MEPE} = 5$	Contractors $N_C = 9$ $n_C = 9$
My company has not encountered disputes with BIM implementation	14 (56%)	3 (100%)	7 (70%)	4 (80%)	6 (67%)
Intellectual property ownership of the model o r parts thereof	2 (8%)	1 (33.3%)	1 (10%)	0 (0%)	2 (22%)
Disputes regarding liability for system designs	8 (32%)	0 (0%)	3 (30%)	1 (20%)	1 (11%)
Adequate compensation for BIM work	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Lack of BIM use from other disciplines	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Level of model accuracy	0 (0%)	0 (0%)	1 (10%)	0 (0%)	0 (0%)

Note. *Select all that apply. Percent (%) = number of selections divided by number of respondents for a specific discipline. Total $N = 52$ and total $n = 56$.

benefits that were found by previous studies on commercial buildings but were not selected by the majority of the participants in our research. Thus, our study did not find that BIM was beneficial on educational facility projects in terms of allowing more time for design instead of creating contract documents, reducing production and construction costs, improving construction safety, and encouraging sustainability efforts. Similar to the previous research on commercial buildings, our study on educational facility projects did not find BIM beneficial for encouraging use of other technologies, increasing project profitability, and allowing for long-term data assessment. On the other hand, our study contributed to the body of knowledge by identifying the following four new benefits specific to educational facility projects that were not mentioned in the previous research: BIM enabling faster reviews for approvals and permits, facilitating modular construction, reducing on-site waste and material use, and providing more accurate as-builts (see italics in Table 13).

Table 13: Comparison of current findings and previous research: benefits of BIM use.

Project phase	BIM benefits	Current findings: BIM use on educational buildings	Previous research: BIM use on general type of the buildings
Design phase	Evaluates the impact of different design solutions	✓	Bynum et al. [57]
	Allows more time to be spent on design than on contract documentation		Cefrio [9], Korman and Lu [46]
	Lowers risk and better predicts outcomes due to discovery of errors, omissions and conflicts prior to construction	✓	U.S. General Service Administration (GSA) [43]
	Enables automation of documentation (better accuracy and accounts for adjustments and changes automatically)	✓	Bynum et al.[57]
	Enables faster reviews for approvals and permits	✓	
Construction phase	Reduces RFI's, change orders, claims, and conflicts	✓	Azhar [39], Ahn et al. [7], Cao et al. [44], Porwal and Hewage [59], Kraling and Dunbar [60]
	Reduces construction and production costs		Ahn et al. [7], Hamdi and Leite [45], Dodge Data and Analytics [47]
	Reduces project delivery time	✓	Ahn et al. [7], Hamdi and Leite [45], Dodge Data and Analytics, [47]
	Facilitates modular construction	✓	
	Increase prefabrication	✓	Ahn et al. [7], Eastman et al. [8]
	Reduces on-site waste and materials use	✓	
	Improves construction safety		Ahn et al. [7], Ganbat et al. [51]
Both design and construction phases	Increases client engagement and provides clearer understanding of 3D visualizations	✓	McGraw Hill Construction [42], Ganbat et al. [51], Arayici et al. [63], Azhar [39]
	Increases productivity and efficiency	✓	Cefrio [9], Chelson [53], Poirier et al. [54], Barlish and Sullivan [55], Nath et al. [56]
	Encourages consideration for sustainable building systems that conserve energy		Bynum et al. [57]
	Serves as a new marketing tool for firms	✓	Ahn et al. [7], Bernstein [61]
	Encourages use of other technologies (GIS, unity, etc.)		
Both construction and O&M phases	*Provides more accurate as-built deliverables*	✓	
All project phases	Improves collaboration and communication between disciplines due to more reliable and direct data exchange from a single resource of information	✓	Bynum et al. [57], Eastman et al. [8]
	Increases project profitability		
	Allow for long term data assessment		

Table 14 shows the comparison of our study and previous research regarding obstacles that prevent BIM use. The analysis of the results is performed using the data presented in Table 11. Similar to the benefit comparison, if majority of the disciplines in our study thought that the obstacles shown in Table 11 are likely (that is, mean score was larger than 3.00) to impede BIM implementation, the check mark was assigned to that specific obstacle in Table 14. Six obstacles identified in previous research on commercial buildings were also confirmed by our research on BIM use in educational facility projects. There were a few obstacles to BIM use that the participants of this research did not

Table 14: Comparison of current findings and previous research: obstacles to BIM use.

Obstacle category	Obstacles that prevent BIM use	Current findings: BIM use on educational buildings	Previous research: BIM use on general type of the buildings
Cost	Cost of software and new hardware to keep up with the software	✓	Lee et al. [3], Gheisari and Irizarry [4], Ahn et al. [7], Won et al. [22], Ganbat et al. [51], Samuelson and Björk [52]
	Cost of hiring experienced staff	✓	
	Lack of substantial quantifiable benefits and evaluation methods	✓	Won et al. [22], Smith [65]
	Fast-paced and small-sized projects do not justify the time needed for the cost of implementing BIM	✓	
Demand	*Not enough owner demand*	✓	
BIM professionals	Lack of expertise and need for training	✓	Lu et al. [1], Gheisari and Irizarry [4], Ahn et al. [7], Won et al. [22], Ganbat et al. [51], Samuelson and Björk [52], Lee et al. [3], Cefrio [9], Gu and London [23]
	Unclear responsibilities, assigned roles, and BIM deliverables	✓	Lee et al. [3], Gu and London [23], Hamdi and Leite [45]
BIM process	*Disruption in workflow to implement new BIM processes*	✓	
	Vulnerability or security of file sharing		Won et al. [22], Ganbat et al. [51]
	Lack of software interoperability	✓	Gheisari and Irizarry [4], Miettinen and Paavola [25], Ganbat et al. [51], Cao et al. [44], Hamdi and Leite [45]
Legal issues	*Lack of BIM standards*	✓	
	Lack of precedence, established laws, and regulations about BIM use		Hamdi and Leite [45]
	Legal liabilities of the BIM process	✓	Lee et al. [3], Ahn et al. [7], Eastman et al. [8]

identify on educational projects as compared to the previous studies. These obstacles include vulnerability or security of file sharing and lack of precedence, established laws, and regulations about BIM use. The contribution of our study is in discovering five new obstacles that the study participants thought were specific to educational facility projects and that were not mentioned in the previous research on commercial buildings. These obstacles relate to cost of hiring experienced staff, fast-paced and small-sized projects not justifying the time needed for the cost of implementing BIM, insufficient owner demand, disruption in workflow to implement new BIM processes, and lack of BIM standards (see italics in Table 14).

6. Conclusions

This study investigated the use of BIM by the AEC industry on educational facility projects in the USA. The objectives were to determine perceptions of the design and construction professionals about BIM adoption by companies, BIM implementation on projects, benefits of using BIM, and obstacles that hinder BIM adoption. A survey was sent to the members of professional organizations such as AIA, AGC, ABC, and ASCE across the USA. The five disciplines that participated in the survey were architects, site engineers, structural engineers, MEP engineers, and contractors. The survey results revealed the following:

(1) *Majority of the Respondents Use BIM.* BIM use was prevalent on educational facility projects according to the professionals from all five disciplines. The majority of those respondents who did not use BIM would be interested in implementing BIM in the future except the architects that indicated having no interest in using BIM. The MEP engineers, site engineers, and architects stated that about half of the employees in their companies were BIM-savvy while the structural engineers and contractors came from the companies with a smaller proportion of BIM-knowledgeable employees. Most of the designers perceived clients as a driving force for BIM implementation which is an important finding in the case of educational projects in which input from the clients (e.g., students, teachers, and principals) is crucial during the design phase.

(2) *The Major BIM Applications on Educational Facility Projects by All Five Disciplines Are 3D Visualizations, Automation of Documentation, and Clash Detection.* As expected, the major BIM applications by a discipline were based on the discipline's scope of work. For example, the structural and site engineers used BIM for structural analysis, the MEP engineers for MEP analysis, and the contractors used BIM for clash detection on the majority of the educational facility projects.

(3) *BIM-Based Collaborative Knowledge Sharing among the Various Project Stakeholders Is Driven by the Educational Facility Project Phase and the Discipline's Scope of the Work.* BIM as a process/methodology requires a collaborative workflow. As expected, due to this workflow and the scope of each discipline work, the large majority of the engineers and the largest proportion of contractors shared the information primarily with architects. The designers and contractors also shared the information with owners indicating that BIM creates collaborative and inclusive environment on educational projects, which also integrates clients into the process.

(4) *BIM Use Is Beneficial in All the Phases of the Educational Facility Projects.* The architects and site engineers thought that the use of BIM was providing value in the design phase of a project while the structural engineers and contractors saw the benefits of BIM use in both design and construction phases of the projects. The MEP engineers thought that BIM use was almost equally valuable in all the project phases. All disciplines agreed that the use of BIM as a new marketing tool and use of 3D models for clearer visualization and understanding of the projects by the clients are some of the most important benefits of BIM. In terms of the other potential benefits, the perceptions varied among the five disciplines due to their specific scope of work. For example, architects indicated that BIM helped them with evaluating different design alternatives and reducing numbers of errors and omissions early on in the project, while the contractors valued highly the use of BIM for increasing productivity and efficiency and decreasing cost and duration of the educational facility projects.

(5) *Regarding the Specific Obstacles That Could Prevent the BIM Use on Educational Facility Projects, the Majority of Respondents Indicated a Few Obstacles as Compared to BIM Benefits.* The architects, site engineers, and MEP engineers thought that BIM-related personnel issues would hinder BIM use, while for the contractors, the cost of BIM implementation was the major barrier to BIM use. According to the structural engineers, lack of substantial quantifiable benefits and evaluation methods would very likely hinder BIM use. Regarding legal disputes related to BIM use, most of the respondents stated that their companies have not encountered disputes with BIM implementation.

(6) *Comparison of the Findings of Our Study That Focused on Educational Facility Projects and the Previous Research That Investigated All Building Project Types Showed That Most of Our Findings on BIM Benefits and Obstacles to BIM Use Correspond to the Findings of Previous Research That Investigated All the Building Types.* However, our study identified four new benefits (i.e., BIM enables faster reviews for approvals and permits, facilitates modular construction, reduces on-site waste and material use, and provides more accurate as-builts) as well as five new obstacles (i.e., cost of hiring experienced staff, fast-paced and small-sized projects not justifying the use of BIM, insufficient owner demand, disruption in workflow to implement new BIM processes, and lack of BIM standards). These factors are specific to the educational facility projects and their discovery represents one of the major contributions of our study.

The contribution of this research is in filling the gap in literature that relates to BIM use specifically on educational facility projects. The study showed prevalence of BIM use on educational projects, possible applications, and how BIM could improve collaborative knowledge sharing among architects, engineers, contractors, and clients, leading to better quality educational buildings. The findings of the study could be utilized by AEC companies in their efforts to implement BIM on educational facility projects.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

There are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge support for the article processing fee from the University of Florida and the Colorado State University libraries open access research and scholarship fund.

Supplementary Materials

Supplementary materials include Appendix A, showing the survey instrument that was distributed to the participants of this research study. (*Supplementary Materials*)

References

[1] Y. Lu, L. Yongkui, M. Skibnievski, Z. Wu, R. Wang, and Y. Le, "Information and communication technology applications in architecture, engineering, and construction organizations: a 15-year review," *Journal of Management in Engineering*, vol. 31, no. 1, article A4014010, 2015.

[2] C. Botton and D. Forgues, "Practices and processes in BIM projects: an exploratory case study," *Advances in Civil Engineering*, vol. 2018, Article ID 7259659, 12 pages, 2018.

[3] S. Lee, J. Yu, and D. Jeong, "BIM acceptance model in construction organizations," *Journal of Management in Engineering*, vol. 31, no. 3, article 04014048, 2015.

[4] M. Gheisari and J. Irizarry, "Investigating human and technological requirements for successful implementation of a BIM-based mobile augmented reality environment in facility management practices," *Facilities*, vol. 34, no. 1/2, pp. 69–84, 2016.

[5] J. Wang, X. Wang, J. Wang, P. Yung, and G. Jun, "Engagement of facilities management in design stage through BIM:

framework and a case study," *Advances in Civil Engineering*, vol. 2013, Article ID 189105, 8 pages, 2013.
[6] Y. Liu, S. van Nederveen, C. Wu, and M. Hertogh, "Sustainable infrastructure design framework through integration of rating systems and building information modeling," *Advances in Civil Engineering*, vol. 2018, Article ID 8183536, 13 pages, 2018.
[7] Y. Ahn, H. Kwak, and J. Suk, "Contractors' transformation strategies for adopting building information modeling," *Journal of Management in Engineering*, vol. 32, no. 1, article 05015005, 2016.
[8] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*, John Wiley and Sons, Hoboken, NJ, USA, 2nd edition, 2011.
[9] Cefrio, *Improving Efficiency and Productivity in the Construction Sector through the Use of Information Technologies*, NRC Industrial Research Assistance Program, Quebec, Canada, 2011.
[10] R. Borden, *"Taking School Design to Students", National Clearinghouse for Educational Facilities*, National Institute of Building Sciences, Washington, DC, USA, 2004.
[11] J. Cohen, *Integrated Project Delivery: Case Studies*, AIA California Council, Sacramento, CA, USA, 2010.
[12] Neasden Primary School, *Application of BIM in Energy Management of Individual Departments Occupying University Facilities*, Neasden Primary School, Hull, UK, 2019, https://neasdenprimary.org.uk/school-new-build/.
[13] Dezeen, *Visual Arts Building Animation*, Iowa University School of Art & Art History, Iowa City, IA, USA, 2019, https://vimeo.com/76039896.
[14] Tigard-Tualatin School District, *Video Walkthrough Released for Tualatin HS Design*, Tigard-Tualatin School District, Tigard, OR, USA, 2019, https://www.ttsdschools.org/site/default.aspx?PageType=3&DomainID=21&ModuleInstanceID=10379&ViewID=6446EE88-D30C-497E-9316-3F8874B3E108&RenderLoc=0&FlexDataID=16640&PageID=63.
[15] J. Zhang and R. Issa, "Collecting fire evacuation performance data using BIM-based immersive serious games for performance-based fire safety design," in *Proceedings of the 2015 International Workshop on Computing in Civil Engineering*, pp. 612–619, Austin, TX, USA, June 2015.
[16] E. Vaughan, *"Elementary School", Whole Building Design Guide*, National Institute of Building Sciences, Washington, DC, USA, 2017, available at: https://www.wbdg.org/building-types/education-facilities/elementary-school.
[17] H. Eckerlin, "An Evaluation of Daylighting in Four Schools in the Research Triangle Area of North Carolina," A Summary Report, North Carolina State University, Raleigh, NC, USA, 2005.
[18] Innovative Design, *Guide for Daylighting Schools, Lighting Research Center*, Rensselaer Polytechnic Institute, Troy, NY, USA, 2004.
[19] K. Tu and D. Vernatha, "Application of Building Information Modeling in energy management of individual departments occupying university facilities," *World Academy of Science, Engineering and Technology International Journal of Architectural and Environmental Engineering*, vol. 10, no. 2, 2016.
[20] H. Gocke and K. Gocke, "Integrated system platform for energy efficient building operations," *Journal of Computing in Civil Engineering*, vol. 28, no. 6, article 05014005, 2014.
[21] J. Irizarry, M. Gheisari, G. Williams, and K. Roper, "Ambient intelligence environments for accessing building information," *Facilities*, vol. 32, no. 3/4, pp. 120–138, 2014, https://doi.org/10.1108/F-05-2012-0034.
[22] J. Won, G. Lee, C. Dossick, and J. Messner, "Where to focus for successful adoption of building information modeling within organization," *Journal of Construction Engineering and Management*, vol. 139, no. 11, article 04013014, 2013.
[23] N. Gu and K. London, "Understanding and facilitating BIM adoption in the AEC industry," *Automation in Construction*, vol. 19, no. 8, pp. 988–999, 2010.
[24] H. Son, S. Lee, and C. Kim, "What drives the adoption of building information modeling in design organizations? An empirical investigation of the antecedents affecting architects' behavioral intentions," *Automation in Construction*, vol. 49, pp. 92–99, 2015.
[25] R. Miettinen and S. Paavola, "Beyond the BIM utopia: approaches to the development and implementation of building information modeling," *Automation in Construction*, vol. 43, pp. 84–91, 2014.
[26] A. Nical and W. Wodynski, "Enhancing facility management through BIM 6D," *Procedia Engineering*, vol. 164, pp. 299–306, 2016, https://www.sciencedirect.com/science/article/pii/S1877705816339649. 10.1016/j.proeng.2016.11.623.
[27] M. Kassem, G. Kelly, N. Dawood, M. Serginson, and S. Lockley, "BIM in facilities management applications: a case study of a large university complex," *Built Environment Project and Asset Management*, vol. 5, no. 3, pp. 261–277, 2015, https://doi.org/10.1108/BEPAM-02-2014-0011.
[28] J. J. McArthur, "A building information management (BIM) framework and supporting case study for existing building operations, maintenance and sustainability," *Procedia Engineering*, vol. 118, pp. 1104–1111, 2015, https://www.sciencedirect.com/science/article/pii/S1877705815021050.10.1016/j.proeng.2015.08.450.
[29] S. Lockley, *BIM for Facilities Management—University Campus*, OpenBIM, Newcastle-upon-Tyne, UK, 2013.
[30] D. Budds, *How Building Information Modeling saved one University $10 Million*, Co. Design, 2017.
[31] C. Keegan, *Building Information Modeling in Support of Space Planning and Renovation in Colleges and Universities*, Master thesis, Worcester Polytechnic Institute, Worcester, MA, USA, 2019, https://web.wpi.edu/Pubs/ETD/Available/etd-042910-162540/unrestricted/CKeegan_Thesis_BIM.pdf.
[32] B. Skripac, *Defining a Holistic, Owner-Driven BIM Project Delivery Standard at the Ohio State University*, CannonDesign, Grand Island, NE, USA, 2019, https://www.cannondesign.com/news-insights/white-papers/defining-a-holistic-owner-driven-bim-project-delivery-standard-at-the-ohio-state-university/.
[33] Indiana University, *BIM Guidelines & Standards for Architects, Engineers, and Contractors*, Indiana University, Bloomington, IN, USA, 2019, http://www.indiana.edu/~uao/docs/standards/IU%20BIM%20Guidelines%20and%20Standards.pdf.
[34] University of Illinois, *Building Information Modeling (BIM) Requirements, Version 1.1*, University of Illinois, Champaign, IL, USA, 2019, available at: http://www.fs.illinois.edu/docs/default-source/facility-standards/bim-requirements.pdf?Status=Temp&sfvrsn=4.
[35] Western Michigan University, *BIM Project Execution and Standards Guide for Western Michigan University Facility Management, V. 14*, Western Michigan University, Kalamazoo, MI, USA, 2019, http://www.fm.wmich.edu/ap/sg/guidelines/Admin_GUIDELINEs_WMU%20BIM%20Execution%20Plan_V14_current.pdf.

[36] University of Southern California, *Building Information Modeling (BIM) Guidelines, Version 1.6*, University of Southern California, Los Angeles, CA, USA, 2019, http://facilities.usc.edu/uploads/documents/cas/BIMGuidelines_VS1_6_2012.pdf.

[37] Virginia Commonwealth University, *Building Information Modeling (BIM) Guidelines and Standards for Architects, Engineers, and Contractors*, Virginia Commonwealth University, Richmond, VA, USA, 2019, https://fmd.vcu.edu/media/fmd/docs/VCUBIMGuidelines-02072014.pdf.

[38] National Institute of Building Sciences (NIBS) Buildingsmart Alliance, "National BIM standard—United States version 3," 2019, https://www.nationalbimstandard.org/.

[39] S. Azhar, "Building information modeling (BIM): trends, benefits, risks and challenges for the AEC industry," *Journal of Leadership and Management in Engineering*, vol. 11, no. 3, pp. 241–252, 2011.

[40] McGraw Hill Construction, "SmartMarket Report: the business value of BIM in North America," McGraw Hill Construction, Research & Analytics, Bedford, MA, USA, 2012.

[41] McGraw Hill Construction, "SmartMarket Report: the business value of BIM for construction in major global markets," McGraw Hill Construction, Research & Analytics, Bedford, MA, USA, 2014.

[42] McGraw Hill Construction, "SmartMarket Report: the business value of BIM for owners," McGraw Hill Construction, Research & Analytics, Bedford, MA, USA, 2014.

[43] U.S. General Service Administration (GSA), *GSA Building Information Modeling Guide Series 01—Overview*, General Services Administration, Washington, DC, USA, 2007.

[44] D. Cao, G. Wang, H. Li, M. Skitmore, T. Huang, and W. Zhang, "Practices and effectiveness of building information modelling in construction projects in China," *Automation in Construction*, vol. 49, pp. 113–122, 2015.

[45] O. Hamdi and F. Leite, "Conflicting side of building information modeling implementation in the construction industry," *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, vol. 6, no. 3, article 03013004, 2014.

[46] T. Korman and N. Lu, "Innovations and improvements of MEP systems for modular construction using building information modeling," in *Proceedings of the Architectural Engineering Conference (AEI)*, pp. 448–455, Oakland, CA, USA, April 2011.

[47] Dodge Data and Analytics, *SmartMarket Brief: BIM Advancements*, Dodge Data and Analytics, New York, NY, USA, 2019, http://www.smartmarketbrief.com/.

[48] T. Kotwal, R. Ponoum, and J. Brodrick, "BIM for energy savings," *ASHRAE Journal*, vol. 53, pp. 81–86, 2011.

[49] D. Lee, J. Park, and S. Song, "BIM-based construction information management framework for site information management," *Advances in Civil Engineering*, vol. 2018, Article ID 5249548, 14 pages, 2018.

[50] McGraw Hill Construction, "SmartMarket report: the business value of BIM for infrastructure," McGraw Hill Construction, Research & Analytics, Bedford, MA, USA, 2012.

[51] T. Ganbat, H.-Y. Chong, P.-C. Liao, and Y.-D. Wu, "A bibliometric review on risk management and building information modeling for international construction," *Advances in Civil Engineering*, vol. 2018, Article ID 8351679, 13 pages, 2018.

[52] O. Samuelson and B.-C. Björk, "A longitudinal study of the adoption of IT technology in the Swedish building sector," *Automation in Construction*, vol. 37, pp. 182–190, 2014.

[53] D. Chelson, *The effects of building information modeling on construction site productivity*, Ph.D. Dissertation, University of Maryland, College Park, MD, USA, 2010.

[54] E. A. Poirier, S. Staub-French, and D. Forgues, "Measuring the impact of BIM on labor productivity in a small specialty contracting enterprise through action-research," *Automation in Construction*, vol. 58, pp. 74–84, 2015.

[55] K. Barlish and K. Sullivan, "How to measure the benefits of BIM—a case study approach," *Automation in Construction*, vol. 24, pp. 149–159, 2012.

[56] T. Nath, M. Attarzadeh, R. L. K. Tiong, C. Chidambaram, and Z. Yu, "Productivity improvement of precast shop drawings generation through BIM-based process re-engineering," *Automation in Construction*, vol. 54, pp. 54–68, 2015.

[57] P. Bynum, R. R. A. Issa, and S. Olbina, "Building information modeling in support of sustainable design and construction," *Journal of Construction Engineering and Management*, vol. 139, no. 1, pp. 24–34, 2013.

[58] K. Lee and S. Choo, "A hierarchy of architectural design elements for energy saving of tower buildings in Korea using green BIM simulation," *Advances in Civil Engineering*, vol. 2018, Article ID 7139196, 13 pages, 2018.

[59] A. Porwal and K. N. Hewage, "Building information modeling (BIM) partnering framework for public construction projects," *Automation in Construction*, vol. 31, pp. 204–214, 2013.

[60] R. K. Kraling and M. Dunbar, "Building information modeling and educational projects," *Engineered Systems*, vol. 28, no. 8, pp. 30–36, 2011.

[61] H. Bernstein, "New research shows contractors are big BIM users," *Engineering News-Record*, 2012.

[62] Z. Shen and L. Jiang, "An augmented 3D iPad mobile application for communication, collaboration and learning (CCL) of building MEP systems," in *Proceedings of the 2012 International Conference on Computing in Civil Engineering*, pp. 204–212, Clearwater Beach, FL, USA, June 2012.

[63] Y. Arayici, P. Coates, L. Koskela, M. Kagioglou, C. Usher, and K. O'Reilly, "Technology adoption in the BIM implementation for lean architectural practice," *Automation in Construction*, vol. 20, no. 2, pp. 189–195, 2011.

[64] D. B. Arensman and M. E. Ozbek, "Building information modeling and potential legal issues," *International Journal of Construction Education and Research*, vol. 8, no. 2, pp. 146–156, 2012.

[65] D. K. Smith, "The USC school of cinematic arts: the arrival of spring in the facilities industry," *Journal of Building Information Modeling*, vol. 2009, pp. 16-17, 2009.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 1267048, 9 pages
https://doi.org/10.1155/2019/1267048

Research Article

Synergistic Effect of Integrated Project Delivery, Lean Construction, and Building Information Modeling on Project Performance Measures: A Quantitative and Qualitative Analysis

Phuong Nguyen[1] and Reza Akhavian[2]

[1]*Department of Civil, Environmental and Architectural Engineering, University of Kansas, 1530 W. 15th Street, 2150 Learned Hall, Lawrence, KS 66045, USA*
[2]*School of Engineering, California State University, East Bay, 25800 Carlos Bee Blvd, Hayward, CA 94542, USA*

Correspondence should be addressed to Reza Akhavian; reza.akhavian@csueastbay.edu

Received 21 January 2019; Revised 19 April 2019; Accepted 23 June 2019; Published 1 July 2019

Guest Editor: Tatjana Vilutiene

In the recent years, owners and construction management companies have shown an increasingly more interest in adopting approaches that result in enhanced quality and less risks, conflicts, and wastes on their projects despite potentially higher initial cost. Implementing advanced technology trends and incorporating more integrated methods of delivering projects have proven to be highly value-adding and forward-thinking approaches. The objective of this research was to evaluate the effectiveness of and the synergy between three of such trending concepts in the construction industry, namely, integrated project delivery (IPD), lean principles, and building information modeling (BIM) in terms of cost and schedule performance measures. Data analysis was conducted on 72 vertical projects through interviews and study of the published articles, reports, and case studies. Qualitative analysis was performed through grounded theory while quantitative analysis was implemented using univariate and multivariate analysis of variance tests on schedule performance and cost performance. Results of the grounded theory analysis summarize six crucial characteristics required for an effective coordination between IPD, lean construction, and BIM. Statistical analysis on different combination of these three components revealed considerable effectiveness in terms of schedule performance while the effect on cost performance was not as much significant. This study contributes to the body of knowledge and practice in the field of construction by demonstrating the cost and schedule benefits realized through the use of IPD, lean construction, and BIM and identifying their collective conceptual advantages.

1. Introduction

The US construction industry experienced 6% performance (approximately $712 billion) in value and achieved 13% increase in the financial profit in 2016 [1]. It is predicted that construction industry's value will be consistently growing with the advancement of modern technologies and adoption of integrated approaches to improve construction performance measures [2]. Construction project cost and schedule are difficult to predict accurately due to complexity of procedures and the presence of various uncertain variables throughout a project. As a result, forecasting and envisioning project cost and schedule performance measures are complicated even for experienced construction experts and professionals [2]. As such, many researchers have been trying to find and recommend the factors that can influence project cost and schedule in a positive way. Many such recommendations are proposed to improve project quality, reducing total costs and time to build, and achieving the most desirable value. Furthermore, regardless of the project delivery method, construction project owners show significantly increased interest in employing technology trends such as building information modeling (BIM), sensor-based resources tracking, automation and robotics, and machine learning [3–5]. In addition to the technological advancement, the industry has come to a general agreement on the value of implementing lean principles while benefiting from the advantages of early coordination and communication between project parties [6]. The latter, has commonly characterized itself via a trending project delivery method, the integrated project delivery (IPD). In the US construction industry, use of IPD necessitates benefiting from advanced techniques including BIM and lean practices [7, 8]. In IPD projects, members meet regularly in early stages of the project initiation where they deliberately discuss relevant issues and practically streamline critical tasks related to the design and construction stages [9]. Not only do such methodologies guarantee lower number of changes and higher levels of confidence in adhering to the original project budget and duration estimate, they also tend to result in more sustainable and resilient outcomes. The motivating questions of this study are as follows:

(1) How can the three components, IPD, BIM, and lean construction be efficiently used in construction projects?

(2) What are cost and schedule implications of projects that utilized a combined framework of IPD, BIM, and lean construction?

This research study aims to investigate the cooperative relationship and efficiency of different combinations of IPD, lean construction, and BIM in improving the performance of construction projects in the U.S. construction industry. Towards this goal, the efficiency of construction projects benefiting from integrated frameworks including different combinations of IPD, lean principles, and BIM (ILB in short hereinafter) is explored in 72 vertical construction projects and case studies. Qualitative and quantitative analyses were employed to evaluate the projects' cost and schedule performance. Three key phases of a construction project, namely, preconstruction (planning, predesign, estimating costs, schematic design, and constructability review), construction (managing constructing process, tracking project schedule, and controlling costs), and postconstruction (project closeout work and completion) are specifically investigated using the proposed evaluation model.

2. Literature Review

A number of recent research studies have discussed the use of IPD, lean construction, and BIM in the US construction industry while there are few projects focusing on investigating the mixed use of all IPD, lean principles, and BIM in terms of project performance metrics, such as cost and schedule performance. In this section, the definition of each component of the ILB integration as described in the construction literature is provided and then the recent research concentrating on the use of all three components in projects are discussed.

2.1. Integrated Project Delivery. According to the American Institute of Architects (AIA), IPD is an important concept in the modern construction that brings together people to examine different building systems through various means of business practices in a collaborative environment [9]. It provides two contractual conceptions: multiparty agreements (MPA) and single purpose entity (SPE) [10]. These concepts refer to the equal distribution of risks and rewards of project-involved parties and requiring an early participation of all involved parties [7, 11]. The main purpose of IPD is to resolve several considerable weaknesses of common project delivery methods such as unassured productivity levels, deficiencies in managing schedule and budget, inadequate information in specifications and drawings, and high level of materials' wastage [12].

2.2. Lean Construction. In the 1990s, recognized as an outcome of the Toyota Production System (TPS), lean manufacturing (or lean production) was established and executed with significant achievements that led to the original uses of lean thinking in the construction industry [13–15]. Since lean principles were originally appeared as a philosophy, it can be defined in many different ways in accordance with the purpose of the users [16–18]. Lean in construction is described as a method to design a construction system to immensely lessen waste of time, materials, and effort in the interest of maximizing possible project value [19, 20]. Lean thinking concentrates on identifying and setting up expected targets and attempts to streamline the master plan. Transforming from lean production, there are three unique concepts of lean principles that construction professionals have identified and evolved: the last planner system, target value design, and lean project delivery system [17, 21–23]. In addition, a variety of means and techniques related to these three concepts are utilized in the construction industry, such as integrated lean project delivery (ILPD), A3 report, lean process design, just-in-time and off-site fabrication, value stream mapping, visual site associated with the 5S principle, daily team cluster, and plan-do-check-adjust procedure [24–26].

2.3. Building Information Modeling. BIM is defined as digital representation of a facility illustrating accurate geometry and pertinent data used for supporting the project's fabrication, construction, and procurement work [6, 27]. Building information models also encompass exchangeable data or files used to assist communication and decision making processes [28]. The term 4D BIM refers to adding time dimension or schedule-related information into the 3D BIM model (usually 3D computer-aided design or CAD) of the project [29]. With the use of simulation in 4D models, many construction conflicts, design clashes, and constructability issues can be found and resolved in advance [30]. 5D BIM is another variation of BIM models developed to incorporate the cost dimension [31]. 5D BIM is still in its infancy stage of practice, and 6D BIM, which has all data of the project's lifecycle management, is forthcoming in practice [32, 33]. All such BIM-centric concepts are useful for any kind of project delivery method. BIM software is varied due to the complexity of its usages and types of project [27, 34]. BIM implementation in the US involves virtual design and construction (VDC) concepts and theories [35–37].

There are many studies about the coordination between IPD and BIM or lean construction and BIM but the particular integration of these three elements has not yet been studied. This is while many construction firms try to combine the functions of each component in order to boost the productivity of their projects [38–40]. In order to successfully integrate IPD, lean construction, and BIM, a collection of their essential conceptions and a detailed analysis of such combination are critical.

2.4. Current Studies on the Integration of IPD, Lean Construction, and BIM in Construction. The current construction literature associated with the integration of IPD, lean construction, and BIM is limited, and existing studies mostly focus on qualitative approaches. As one of the first qualitative studies related to implementing BIM in conjunction with lean principles and IPD, Miettinen and Paavola [41] conducted a position literature study outlining developments and enhancements of this cooperation. As a result, they proposed two conceptual frameworks, namely, normative and the activity—theoretical/evolutionary, where BIM can be utilized together with other management tools and project concepts. Rokooei [42] affirmed that the use of the BIM-based IPD approach supports the project team to keep track and review the project in addition to making important decisions and resolving potential conflicts to enhance the project execution. Another study showed that BIM utilization enables collaborative lean construction exercises extensively; in fact, BIM users experience leaner procedures by minimizing waste and maximizing value and are more able to deal with potentially complex conflicts and threats to project success [43]. In a theoretical approach to analyze the collaboration between IPD and BIM, Froese [44] indicated that these two elements can lead to a comprehensive scheme that establishes meaningful and predictable relationships between the time constraint, processes, and products. The aforementioned studies suggest that past efforts using qualitative analyses supports the mixed use of IPD, lean practices, and BIM in improving project performance.

In terms of quantitative approaches, the existing body of knowledge includes research focusing mostly on case studies about the feasibility of using ILB. Using a case study of the first IPD-implemented project, AutoDesk headquarters in San Francisco, California, Kent and Becerik-Gerber [7] concluded that the application of IPD in the construction industry was, at the time, in its infancy, but the utilization of BIM can assist IPD to be more productive and valuable approach. Lee et al. [45] used three real-world projects in California to assess the project performance with the simultaneous implementation of IPD, lean principles, and BIM. Furthermore, many construction professionals and experts believe that BIM application will intensively facilitate lean principles in expanding project performance [22]. Taking into account the improvement of project performance, IPD and lean construction need to be utilized together with a view to improve reliability between project participants and increase true value for everyone [46]. Correspondingly, quantitative approaches in the current construction literature reinforce the integration of IPD, lean practices, and BIM in achieving better project performance.

This research paper, first, conducted the grounded theory for the qualitative part in order to demonstrate how ILB integration can be theoretically achieved. Second, a quantitative approach with multiple statistical testing processes aiming at analyzing how ILB integration was actually implemented in vertical construction projects was proposed. Finally, key findings were summarized to support the discussion points.

3. Research Methodology

This study attempts to fill in the current underlying research gaps of incorporating IPD, lean principles, and BIM by utilizing both qualitative and quantitative approaches to assess ILB-based project performance. Firstly, qualitative research manner was used to gather information and case studies of ILB in the current construction industry which leads to a summary of how to use ILB and its structure. Secondly, quantitative research manner was executed with multiple statistical testing in order to assess proposed hypotheses. Lastly, a detailed discussion was performed.

3.1. Data Collection. Initially, data regarding 76 vertical construction projects with a variety of use cases, including healthcare, educational, commercial, military, and industrial, were collected via phone interviews, emails, published articles, construction firms' websites, and other online sources. Due to the nature of some projects and according to the nondisclosure agreements (NDA) between the owner and contractors, several data sources are required to be kept confidential. The phone interviews took place with participations of numerous construction professionals from 36 general contractor firms in the US. After cleaning the collected data (i.e., removing missing data points and extreme outliers), data regarding 72 projects were prepared to proceed with the qualitative and quantitative analyses. The majority of the data pertained to healthcare (61.84%) followed by commercial (9.21%) and educational (9.21%) projects.

Table 1 shows descriptive statistics of collected data with 55 IPD-utilized, 70 BIM-employed, and 54 lean-based projects. Turner Construction, DPR Construction, and Clark Construction were the top three firms that provided the majority of the collected data.

3.2. Qualitative Analysis. To thoroughly understand the extent of using IPD, BIM, and lean practices in the current US construction industry, a commonly used qualitative method, called the grounded theory, was utilized. Grounded theory is a general methodology to develop theory that is grounded in the data collected systematically about the phenomena of the research [47]. In this case, the phenomenon of the research is ILB combination in order to theoretically assess ILB-based project performance. Due to the fact that there are many different types, definitions, and

Table 1: Descriptive statistics of collected data.

Characteristics	Unit	N	Mean	Median	Max	Min
Project area	sq.ft	72	389,590	200,000	4,000,000	1,600
Planned schedule	Month	72	30	25	125	1
Actual schedule	Month	72	29	24	120	1
Target cost	Million ($)	72	244	124	1,300	0.5
Actual cost	Million ($)	72	240	122	1,298	0.3
Year of completion	Year	72	2012	2013	2019	2007

practices of IPD, BIM, or lean construction in the industry, it is difficult to classify and recognize typical practices of those three methods. The objective of the grounded theory used in this study was to identify and group all common practices of ILB in order to provide a comprehensive view of the current use of ILB in the US construction industry.

According to grounded theory analysis, collected information is initially coded by identifying and naming essential concepts, indicating main phrases, and transforming data into theoretical components. Theorized concepts are needed before preparing the first draft for data analysis. Examined theories are incorporated and refined together with generating conceptual models in order to compare analyzed data and write up complete theories [47]. In this study, qualitative data were collected via phone interviews, emails, and other online materials. Qualitative questions related to definitions, practices, current uses, and benefits of ILB were distributed to collect opinions and subjective judgements of professionals about the use of ILB in vertical construction.

3.3. Quantitative Analysis. In the quantitative analysis part, this study used the following as the null hypotheses for univariate and multivariate statistical tests:

(1) The use of all three components (IPD, BIM, and lean practices) does not statistically significantly affect the cost performance of building construction projects.

(2) The use of all three components (IPD, BIM, and lean practices) does not statistically significantly affect the schedule performance of building construction projects.

(3) The use of all three components (IPD, BIM, and lean practices) does not statistically significantly affect both cost and schedule performance of building construction projects.

In order to analyze the relationships and characteristics of ILB synergies, the descriptive statistics research method that represents the relations of collected variables was applied. Inference statistics theory, such as analysis of variance (ANOVA), generalized linear model (GLM), and data transformation techniques like power transform and natural logarithm are used in this analysis. The Statistical Package for the Social Sciences (SPSS) computer software is employed to perform the statistical testing analyses. A summary of input variables and control factors is presented in Table 2: the first model contains a full ILB integration; the second model contains lean and BIM; and the third model contains IPD and BIM.

Descriptive statistics are employed to calculate the median, mode, mean, maximum, and minimum values of the standard deviation, kurtosis, and skewness of the collected data. Subsequently, analyzed variables are examined by normality tests to determine if the collected data are normally distributed. If normal distribution is not observed, methods of data transformation including power transform, the decimal logarithm, linear transformation, natural logarithm, and inverse distribution functions are used. Afterwards, normally distributed data are classified into three separate models according to Table 1 and analyzed by univariate and multivariate analysis of variance (ANOVA) as well as Duncan's multiple range test (MRT). Duncan's MRT is a multiple comparison process which utilizes an estimating range statistic in order to measure groups of means. The outcomes of these tests demonstrate accurate, detailed, and certain differences of cost performance and schedule performance of analyzed groups in terms of the mean, median, and mode. About thirty projects are grouped for each model based on their characteristics of delivered by IPD, enhanced lean principles, and utilized BIM techniques. Multiple ANOVA tests are carried out to assess the proposed hypotheses while the least square regression is performed by the applying generalized linear models (GLMs). The use of GLM is to assure the reliability of quantitative data in the analytical process.

4. Grounded Theory Implementation

Grounded theory in this study is used to demonstrate ILB cooperation and their effects in enhancing project performance. According to Khan [47], grounded theory analysis includes four main steps as follows:

(i) Stage 1—codes: determining key data and required aspects in order to obtain facts and specific information.

(ii) Stage 2—concepts: clarifying and grouping collected data by considering analogous and mutual concepts.

(iii) Stage 3—categories: developing theories and conceptual models based on immense groups of defined concepts.

(iv) Stage 4—theory: revealing and expounding developed descriptions and concepts in furtherance of making clear study objections.

The first step of this research is to conduct an adequate review of the literature and collect key data related to IPD, lean construction, and BIM use in both synergistic and individual perspectives. The used keywords were "Integrated Project Delivery," "Building Information Modeling," and "Lean practices in construction." In stage 1, a literature review was conducted to determine the IPD-related

Table 2: Analyzing models and control factors.

Model	Variables			Control factors	
	IPD	Lean	BIM	Cost performance	Schedule performance
1	Y	Y	Y	C1	S1
2	—	Y	Y	C2	S2
3	Y	—	Y	C3	S4

concepts, lean practices, and BIM-related themes which were later transferred to stage 2. In stage 2, fourteen concepts associated with the incorporating use of IPD, lean construction, and BIM were gathered from literature reviews, interviews, and online materials and summarized in Table 3. These concepts are the key practices of ILB in the construction industry which certainly impact on the success of implementation of ILB. The lean culture and associated techniques provide state-of-the-art principles of typical lean practices in construction.

After gathering and organizing all ILB-associated data, the analyzed definitions and perceptions were input into a conceptual model that consists of overlaps and commonalities of IPD, lean principles, and BIM using mind-mapping and pattern-matching techniques. This model includes fourteen particular concepts investigated in the earlier section and is constituted into six prime measures used to explain how to enhance project performance with the fourteen conceptual practices of ILB indicated in Table 3. In consideration of clarifying the relationships of every prime measure within the model, the categories' selection (stage 3) and arrangement of collected concepts are demonstrated as follows:

(i) Durable value and continuous development: (1) BIM-4D and BIM-5D; (3) key performance indicators (KPIs); (4) A3 report; (6) project modification or innovation (PMI); (7) value stream mapping and cluster teams; (9) multiparty agreement (MPA); (11) virtual design and construction (VDC); (13) lean culture and other techniques; and (12) set-based design (SBD).

(ii) Customer satisfaction and waste elimination: (1) BIM-4D and BIM-5D; (4) A3 reports; (5) choosing by advantages (CBA); (6) project modification or innovation (PMI); (7) value stream mapping (VSM); (8) last planner system; (9) multiparty agreement (MPA); (10) target value design (TVD); (11) virtual design and construction (VDC); (12) set-based design (SBD); (13) lean culture; and (14) owner participation.

(iii) Communication and achievement metrics: (4) A3 Reports; (5) choosing by advantages (CBA); (6) project modification or innovation (PMI); (7) value stream mapping; (8) last planner system; (9) multiparty agreement (MPA); (11) virtual design and construction (VDC); and (14) owner participation.

(iv) Interrelationship improvement: (2) big room; (4) A3 reports; (5) choosing by advantages (CBA); (6) project modification or innovation (PMI); (8) last planner system; (9) multiparty agreement (MPA); (10) target value design (TVD); and (13) lean culture.

(v) Information transmission and transparency: (3) key performance indicators (KPIs); (4) A3 reports; (5) choosing by advantages (CBA); (7) value stream mapping; (8) last planner system; (9) multiparty agreement (MPA); (11) virtual design and construction (VDC); and (13) lean culture.

(vi) True cooperation and trusts: (2) big room; (6) project modification or innovation (PMI); (7) value stream mapping; (8) last planner system; and (9) multiparty agreement (MPA).

Stage 4 of the grounded theory will be verified through a quantitative approach with descriptive statistics and inferential testing of cost and schedule performances in the next section.

5. Quantitative Data Analysis

5.1. Descriptive Statistics Analysis and Data Normality. The particular descriptive statistics of cost performance and schedule performance used in this paper are means, variance, range, standard deviation, and median. In addition, the normality test was performed as a requirement of assumptions for inference statistics (hypothesis testing) to confirm whether the data are normally distributed or have some degree of symmetry. The skewness test for cost performance returned the value of −7.212 and that of the schedule performance was 2.080. Since neither of the skewness values are in the range of −1 to 1, this distribution is not normal. In addition, the Kolmogorov–Smirnov (K-S) test was used to further verify that the data are not following the normal distribution. The normality Shapiro–Wilk test confirmed that the data pertaining to the two factors are not normally or near-normally distributed. Therefore, data transformation was required to convert and reconstruct the datasets for further statistical analyses.

5.2. Data Transformation and Inferential Statistics Procedure. A two-step mean transformation method was used for converting the continuous variables to the ones normally distributed. The process begins with fractionally ranking variable cases in order to have a consistency for the transformed variable [48]. Subsequently, the inverse normal distribution was employed to transform data distribution with the SPSS software. As a result, the skewness distributions of both cost performance and schedule performance data are adjusted, to satisfy the requirements of normality, uniformity, and linearity of multiple analyzed variances. In addition to the cost performance and schedule performance data transformation, project size (or gross area) was also transformed to be included in the univariate and multivariate ANOVA analyses as well as generalizing linear models in the next step of the data analysis procedure. As a result, the new skewness test statistics for cost performance

Table 3: Synergizing concepts from case studies.

Key analyzing concepts
(1) BIM-4D and 5D with five different levels: visualization, coordination, constructability, fabrication/installation and total cost of ownership
(2) A big room, co-location, small breaks, and track plan percent complete (PPC)
(3) Key performance indicators (KPIs)
(4) A3 reports or rainbow report
(5) Choosing by advantages (CBA)
(6) Project modification or innovation (PMI)
(7) Value stream mapping and cluster teams
(8) The last planner system (e.g., pull planning, master scheduling, weekly work planning, etc.)
(9) Multiparty agreement (MPA) (Consensus-DOCS 300-2008, AIA document A195-2008, A295-2008, B195-2008) and single purpose entity (SPE) (AIA document C195-2008)
(10) Target value design (TVD)
(11) Virtual design and construction (VDC)
(12) Set-based design (SBD)
(13) Lean culture and other techniques (i.e., the "customer-supplier" viewpoint, plan do study act (PDSA), etc.)
(14) Owner participation in ILB

and schedule performance after transformation were 0.03 and 0.06, respectively, which are in the acceptable range of normal and near-normal distribution (i.e., between −1 and 1).

5.3. Measurements of Project Performance Metrics. The use of any project delivery methods, tools, or techniques can be measured by proper project performance in order to adequately assess their efficiency and precisely enhance them. This study utilizes two commonly used measurements for construction projects: cost and schedule performance, which are calculated using the following equation:

$$\begin{aligned} CP &= \frac{(FC - IC) \times 100}{IC}, \\ SP &= \frac{(FD - PD) \times 100}{PD}, \end{aligned} \quad (1)$$

where CP is the cost performance, FC is the final project cost, IC is the initial project cost, SP is the schedule performance, FD is the final duration, and PD is the planned duration. The following section provides descriptive statistics and treatments for nonnormally distributed data of cost performance and schedule performance.

5.4. Cost Performance Analysis. To evaluate the first null hypothesis, adjusted cost performance data as the dependent variable, the five levels of ILB combination as the independent variables, and the adjusted project size as the covariate factor were used for the univariate and multivariate ANOVA tests. With the p value of 0.63 at 95% confidence interval, there was no statistically significant difference between cost performances of the different models. Because of the small sample size, the use of several post hoc tests, including Hochberg's GT2 and Games-Howell process is recommended by Dell et al. [49] to ensure equality of population variances. This setting was applied to the rest of univariate tests. The multiple comparison range tests based on the confidence interval of 95% and examination via two procedures with cost performance dependent variable are shown in Table 4. In particular, the table shows the differences between one combination and the other at 95% confidence interval. In addition, it also indicates the significance of each difference to show the reliability of the comparison. However, there was no statistically significant difference found in pairwise comparisons for combination groups.

According to the results from estimated marginal means and significance (p values), the reliability of the outcomes of the comparison between five combination levels with the cost performance index variable was ensured. As a result, the first null hypothesis is rejected because of the insignificance or p value higher than 0.05 in the univariate test. Notwithstanding the null hypothesis evaluation for cost performance, different projects benefiting from different combinations of IPD, lean construction, and BIM showed interesting results in terms of the cost performance mean. Results of the ANOVA test with the 95% confidence interval for cost performance (with the adjustment for project sizes) indicate that projects that utilize IPD, lean construction, and BIM have the highest value of cost performance compared to other projects.

5.5. Schedule Performance Analysis. In order to evaluate the second null hypothesis, the univariate test for the ILB effects on schedule performance was conducted with SPSS software. Here, adjusted schedule performance data are used as the dependent variables, the five levels of ILB combination serve as the independent variables, and the adjusted project size is used as the covariate factor for the ANOVA tests. In consideration of investigating the differences in schedule performance of five levels, multiple comparison range tests were carried out. Similar to the cost performance's univariate results, a full ILB combination shows a significant mean difference compared to the others which proves that its implementation would have a positive effect on the project's schedule performance as shown in Table 5. The p value (0.008) of this univariate analysis indicates that the null

Table 4: Pairwise comparisons of combination groups in terms of cost performance.

Combination group		Mean difference	Significance (p value)
IPD + Lean + BIM (ILB)	Lean + BIM	0.045	0.909
	IPD + BIM	0.031	0.902
Lean + BIM	ILB	−0.048	0.640
	IPD + BIM	−0.017	0.992
IPD + BIM	ILB	−0.031	0.902
	Lean + BIM	0.017	0.992

Table 5: Pairwise comparisons of combination groups in terms of schedule performance.

Combination group		Mean difference	Significance (p value)
IPD + Lean + BIM (ILB)	Lean + BIM	0.008	0.997
	IPD + BIM	0.058	0.081
Lean + BIM	ILB	−0.008	0.997
	IPD + BIM	0.050	0.271
IPD + BIM	ILB	−0.058	0.081
	Lean + BIM	−0.050	0.271

hypothesis of the significant effect of ILB combination on project schedule performance cannot be rejected. Pairwise comparisons of combination groups in terms of schedule performance do not show significant difference except when the full ILB combination is compared to using only BIM.

As compared the schedule performance values for the projects that used different combinations of ILB components to those of the projects that only employed BIM, full combination of ILB components indicates the highest schedule performance value while using only BIM results in the lowest schedule performance value of all the models.

5.6. Cost and Schedule Performance Analysis. The third null hypothesis is investigated to assess the impact of ILB integration on both cost and schedule performances simultaneously with normalization with respect to the size of projects. As such, a multivariate ANOVA (or MANOVA) test is performed. F-ratio and four measuring statistics, namely, Pillai's trace, Hotelling-Lawley's trace, Wilk's lambda, and Roy's largest root, have been used to test the null hypothesis. These four tests were used in order to ensure the reliability of the multivariate test regarding the statistically significant difference between the three separate models, including ILB, Lean-BIM, and IPD-BIM, in terms of cost performance and schedule performance. Table 6 summarizes the results of the MANOVA test. In particular in this table, values refer to the test statistics of the four models; the F-ratio shows the test reliability; the significance refers to the acceptance/rejection of the research hypothesis, and observed power is another variable which confirms that the results are reliable. According to four distinguishing multivariate tests, p values from 0.005 to 0.03, which are less than 0.05, the third null hypothesis is answered, so a full combination of IPD, lean construction, and BIM will have a significant effect on both cost and schedule performance, considered as a group, with differences in project sizes or gross area. In addition, the F value and hypothesis df show the reliability of these hypothetical tests (Table 6). In particular, the third hypothesis is accepted because of the multivariate result of a full ILB in terms of both cost performance and schedule performance by four statistical tests: Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's largest root. As a result, a full ILB does have a significant effect on both cost performance and schedule performance of construction projects.

Table 6: Multivariate tests.

Variable	Test model	Value	F	Sig.	Observed power
ILB	Pillai's trace	0.219	2.156	0.034	0.838
	Wilks' lambda	0.787	2.199	0.031	0.847
	Hotelling's trace	0.264	2.241	0.028	0.854
	Roy's largest root	0.231	4.038	0.005	0.893

6. Discussion and Conclusion

In this research, 72 real-world construction projects that implemented a subset of IPD, lean principles, and BIM (ILB in short) were studied. Qualitative analysis was performed to identify specific concepts that lead to a successful implementation of ILB using grounded theory. Additionally, six influential aspects of a successful project were outlined in terms of quality, cost, and schedule performance. Developed with a combination of defined concepts and project-specific factors, an ILB checklist was created with supporting evidence. According to that recommended checklist for ILB synergies, unique tools and techniques are summarized and categorized into three key sections related to four main phases of a typical construction project. This classification helps project team members to consider and employ essential factors leading to project success with respect to the leveraging the power of ILB. The cooperative characteristics of the fourteen identified concepts are evaluated during different phases of a construction project, from planning to operation.

In terms of quantitative analysis, descriptive statistics were used to evaluate the effect of ILB integrations on projects' cost performance and schedule performance. Various quantitative and inferential statistics tests were performed, including normality examination, data transformation, and univariate and multivariate ANOVA investigation. According to analyzed outcomes, for projects that implement a full combination of ILB, (1) the effect on the cost performance index was not statistically significant, (2) the effect on the schedule performance index was statistically significant, and (3) the effect on the cost performance index and schedule performance index, collectively, was statistically significant.

This study contributes to the body of knowledge in the general area of construction engineering and management by providing evidence-based indicators of the factors affecting successful implementation of IPD, lean principles, and BIM. With the identification of 14 most common practices of using ILB in the current US construction industry, this study contributes to the body of knowledge by providing contextual information about having all the three components together. This study also contributed to the body of practice by providing an insight about the cost and schedule performance of projects that took advantage of ILB. It also demonstrates the significance of implementing those typical three factors on the cost and schedule performance of the projects using vertical project cases. Future research may evaluate other project performance measures such as the number of request of information (RFI), punch list ratio, and green features implementation. Moreover, future studies can provide designated analysis for different industry sectors such as commercial, residential, and industrial, in separate categories.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

Any opinions, findings, conclusions, and recommendations expressed in this paper are those of the authors and do not necessarily represent those of the ORSP.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The presented work was partially funded by the California State University East Bay (CSUEB) Office of Research and Sponsored Programs (ORSP) Faculty Support Grant (FSG). The authors gratefully acknowledge the support from the ORSP.

References

[1] K. McCook, *Dodge Data and Analytics: 2015-16 Outlook for, U.S. Construction Presentation*, Dodge, Auburn Hills, MI, USA, 2015.

[2] C. Gray and E. Larson, *Project Management*, McGraw-Hill/Irwin, Boston, MA, USA, 5th edition, 2011.

[3] F. Castronovo, B. Awad, and R. Akhavian, "Implementation of virtual design reviews in the generation of as-built information," *Construction Research Congress (CRC)*, 2018.

[4] R. Akhavian and A. Behzadan, "Simulation-based evaluation of fuel consumption in heavy construction projects by monitoring equipment idle times," in *Proceedings of the 2013 Winter Simulations Conference (WSC)*, IEEE, Washington, DC, USA, December 2013.

[5] R. Akhavian and A. Behzadan, "Wearable sensor-based activity recognition for data-driven simulation of construction workers' activities," in *Proceedings of the 2015 Winter Simulations Conference (WSC)*, IEEE, Huntington Beach, CA, USA, December 2015.

[6] N. Dong, A. Khanzode, and H. Lindberg, "Applying lean principles, BIM, and quality control to a construction supply chain management system," in *Proceedings of the 30th CIB W78 International Conference*, Beijing, China, 2013.

[7] D. C. Kent and B. Becerik-Gerber, "Understanding construction industry experience and attitudes toward integrated project delivery," *Journal of Construction Engineering and Management*, vol. 136, no. 8, pp. 815–825, 2010.

[8] I. Tommelein, "Journey toward lean construction: pursuing a paradigm shift in the AEC industry," *Journal of Construction Engineering and Management*, vol. 141, no. 6, article 04015005, 2015.

[9] AIA, *Integrated Project Delivery: Case Studies*, AIA, Hong Kong, China, 2010, http://info.aia.org/aia/ipdcasestudies.cfm.

[10] I. H. El-adaway, "Integrated project delivery case study: guidelines for drafting partnering contract," *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, vol. 2, no. 4, pp. 248–254, 2010.

[11] O. Matthews and G. Howell, "Integrated project delivery an example of relational contracting," *Lean Construction Journal*, vol. 2, no. 1, pp. 46–61, 2005.

[12] R. Ghassemi and B. Becerik-Gerber, "Transitioning to integrated project delivery: potential barriers and lessons learned," *Lean Construction Journal*, pp. 32–52, 2011.

[13] G. Ballard and G. Howell, "What kind of production is construction," in *Proceedings of the 6th International Conference on Lean Construction*, Guaruja, Brazil, 1998.

[14] L. Koskela, *An Exploration Towards a Production Theory and its Application to Construction*, VVT Technical Research Centre of Finland, Espoo, Finland, 2000.

[15] L. Koskela, G. Howell, G. Ballard, and I. Tommelein, "The foundations of Lean construction," in *Design and Construction: Building in Value*, R. Best and G. de Valence, Eds., Elsevier, Amsterdam, Netherlands, In press, 2002.

[16] L. Forbes, S. Ahmed, and D. Batie, "Incorporating lean in CM education to improve the construction industry—proposing a model," in *Proceedings of the 50th ASC Annual International Conference*, Associated Schools of Construction, Washington, DC, USA, March 2014.

[17] L. Forbes and S. Ahmed, *Modern Construction: Lean Project Delivery and Integrated Practices*, CRC Press, Boca Raton, FL, USA, 2011.

[18] L. Koskela, A. Ferrantelli, J. Niiranen, E. Pikas, and B. Dave, "Epistemological explanation of lean construction," *Journal of*

Construction Engineering and Management, vol. 145, no. 2, article 04018131, 2019.

[19] R. Sacks, "Modern construction: lean project delivery and integrated practices," *Construction Management and Economics*, vol. 31, no. 4, pp. 394–396, 2013.

[20] G. Howell and L. Koskela, "Reforming project management: the role of lean construction," in *Proceedings of the 8th Annual Conference of the International Group for Lean Construction*, Brighton, UK, July 2000.

[21] R. Sacks, B. Dave, L. Koskela, and R. Owen, "Analysis framework for the interaction between lean construction and building information modeling," in *Proceedings for the 17th Annual Conference of the International Group for Lean Construction*, Taipei, Taiwan, July 2009.

[22] R. Sacks, L. Koskela, B. A. Dave, and R. Owen, "Interaction of lean and building information modeling in construction," *Journal of Construction Engineering and Management*, vol. 136, no. 9, pp. 968–980, 2010.

[23] H. G. Ballard, *The Last Planner System of Production Control*, School of Civil Engineering, Faculty of Engineering, The University of Birmingham, Birmingham, UK, 2000.

[24] R. Jugulum and P. Samuel, *Design for Lean Six Sigma*, John Wiley and Sons, Hoboken, NJ, USA, 2008.

[25] A. Khanzode, M. Fischer, and D. Reed, "Case study of the implementation of the lean project delivery system (LPDS) using virtual building technologies on a large healthcare project," in *Proceedings of the IGLC-13*, Sydney, Australia, July 2005.

[26] F. Bamana, N. Lehoux, and C. Cloutier, "Simulation of a construction project: assessing impact of just-in-time and lean principles," *Journal of Construction Engineering and Management*, vol. 145, no. 5, article 05019005, 2019.

[27] D. Gerber, B. Becerik-Gerber, and A. Kunz, "Building information modeling and lean construction: technology, methodology and advances from practice," in *Proceedings of the 18th Annual Conference, International Group for Lean Construction*, Haifa, Israel, July 2010.

[28] B. Succar, W. Sher, and A. Williams, "Measuring BIM performance: five metrics," *Architectural Engineering and Design Management*, vol. 8, no. 2, pp. 120–142, 2012.

[29] Y. Jung and M. Joo, "Building information modelling (BIM) framework for practical implementation," *Automation in Construction*, vol. 20, no. 2, pp. 126–133, 2011.

[30] U. Umar, N. Shafiq, A. Malakahmad et al., "4D BIM application in AEC industry: impact on integrated project delivery," *Research Journal of Applied Sciences, Engineering and Technology*, vol. 10, no. 5, pp. 547–552, 2015.

[31] H. Fong, *BIM Development—Hong Kong and World Wide Trend*, Autodesk, Wuhan, China, 2009.

[32] S. Azhar, "Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry," *Leadership and Management in Engineering*, vol. 11, no. 3, pp. 241–252, 2011.

[33] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley and Sons Inc., Hoboken, NJ, USA, 2nd edition, 2012.

[34] S. Liu, B. Xie, L. Tivendal, and C. Liu, "Critical barriers to BIM implementation in the AEC industry," *International Journal of Marketing Studies*, vol. 7, no. 6, p. 162, 2015.

[35] A. Khanzode, M. Fischer, and D. Reed, "Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project," *Itcon*, vol. 13, pp. 324–342, 2008.

[36] A. Khanzode, M. Fischer, D. Reed, and G. Ballard, "A guide to applying the principles of virtual design and construction (VDC) to the lean project delivery process," in *Proceedings of the CIFE Working Paper #093*, Center for Integrated Facility Engineering (CIFE), Stanford, CA, USA, December 2006.

[37] V. Popov, V. Juocevicius, D. Migilinskas, L. Ustinovichius, and S. Mikalauskas, "The use of a virtual building design and construction model for developing an effective project concept in 5D environment," *Automation in Construction*, vol. 19, no. 3, pp. 357–367, 2010.

[38] Z. Hunzeker and D. Selezan, *BIM to the MAX: Applying Lean Construction to IPD Projects Presentation*, Autodesk University, San Francisco, CA, USA, 2015.

[39] B. Hyatt, "A case study in integrating lean, green, BIM into an undergraduate construction management scheduling," in *Proceedings of the 47th ASC Annual International Conference*, Associated Schools of Construction, Fresno, CA, USA, 2011.

[40] M. Moghadam, A. Alwisy, and M. Al-Hussein, "Integrated BIM/lean base production line schedule model for modular construction manufacturing," *Construction Research Congress*, pp. 1271–1280, 2012.

[41] R. Miettinen and S. Paavola, "Beyond the BIM utopia: approaches to the development and implementation of building information modeling," *Automation in Construction*, vol. 43, pp. 84–91, 2014.

[42] S. Rokooei, "Building information modeling in project management: necessities, challenges and outcomes," *Procedia—Social and Behavioral Sciences*, vol. 210, pp. 87–95, 2015.

[43] I. Kjartansdóttir, "*BIM adoption in iceland and its relation to lean construction*," M.S. thesis, Reykjavík University, Reykjavik, Iceland, 2011.

[44] T. M. Froese, "The impact of emerging information technology on project management for construction," *Automation in Construction*, vol. 19, no. 5, pp. 531–538, 2010.

[45] H. W. Lee, H. Oh, Y. Kim, and K. Choi, "Quantitative analysis of warnings in building information modeling (BIM)," *Automation in Construction*, vol. 51, pp. 23–31, 2015.

[46] J. Darrington and W. Lichtig, "Integrated project delivery: aligning project organization, operating system and commercial terms," 2018, https://www.dpr.com/assets/case-studies/IPD-Whitepaper_2018-2.pdf.

[47] S. Khan, "Qualitative research method: grounded theory," *International Journal of Business and Management*, vol. 9, no. 11, 2014.

[48] G. F. Templeton, "A two-step approach for transforming continuous variables to normal: implications and recommendations for IS research," *Communications of the Association for Information Systems*, vol. 28, no. 4, 2011.

[49] R. Dell, S. Holleran, and R. Ramakrishnan, "Sample size determination," *Institute for Laboratory Animal Research Journal*, vol. 43, no. 4, pp. 207–213, 2002.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 9094254, 9 pages
https://doi.org/10.1155/2019/9094254

Research Article

BIM Use Assessment (BUA) Tool for Characterizing the Application Levels of BIM Uses for the Planning and Design of Construction Projects

María J. Rojas,[1] Rodrigo F. Herrera ,[2,3,4] Claudio Mourgues,[3] José L. Ponz-Tienda,[1] Luis F. Alarcón,[3] and Eugenio Pellicer [4]

[1]*Department of Civil and Environmental Engineering, Universidad de Los Andes, Bogotá, Colombia*
[2]*School of Civil Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile*
[3]*Department of Construction Engineering and Management, Pontificia Universidad Católica de Chile, Santiago, Chile*
[4]*School of Civil Engineering, Universitat Politècnica de València, Valencia, Spain*

Correspondence should be addressed to Rodrigo F. Herrera; rodrigo.herrera@pucv.cl

Received 1 February 2019; Revised 27 April 2019; Accepted 22 May 2019; Published 9 June 2019

Academic Editor: Reza Akhavian

The evaluation of BIM capabilities and repeatability enables a company or project to identify its current status and how to improve continuously; this evaluation can be performed with BIM maturity models. However, these maturity models can measure the BIM state but not specifically the application of BIM uses. Likewise, in interorganizational project teams with a diversity of factors from various companies, it is possible to evaluate the capacity at a specified time with specified factors, but it is not possible to evaluate the repeatability unless the client always works with the same project teams. Therefore, despite the existence of various BIM uses in the literature, there is no instrument to evaluate the level of implementation of them in construction projects. This research proposes a BIM Use Assessment (BUA) tool for characterizing the levels of application of the BIM uses in the planning and design phases of building projects. The research methodology was organized into three stages: (1) identification, selection, and definition of BIM uses; (2) proposal of the BUA tool for characterizing the level of BIM use application; and (3) validation of the BUA tool. The tool was validated using 25 construction projects, where high reliability and concordance were observed; hence, the BUA tool complies with the consistency and concordance analysis for assessing uses in the design and planning phases of construction projects. The assessment will enable self-diagnosis, stakeholder qualification/selection, and industry benchmarking.

1. Introduction

Building information modeling (BIM) is becoming an essential methodology in the architecture, engineering, and construction (AEC) industry. Indeed, public agencies from several countries are encouraging the use of this methodology by issuing requirements, user guides, and manuals regarding its use [1]. There are several ways of using BIM (BIM uses), which lead to various benefits; as stated by Kreider and Messner [2], applications of BIM during the infrastructure lifecycle can enable the realization of one or more specific objectives. Therefore, it is important to understand the way that organizations apply BIM uses.

BIM uses are defined in various ways: the Penn State guide defines BIM use as "a method of applying Building Information Modeling during a facility's life cycle to achieve one or more specific objectives" [2]. According to Succar, BIM uses "identify and collate the information, requirements that need to be delivered as—or embedded within—3D digital models" [3]. Another definition comes from the New York guide, which defines BIM uses as "the most common applications of BIM on the Department of Design and Construction Projects; BIM uses shall be considered and aligned with project goals" [4]. Thus, while there is a consensus on the relationship of uses to project objectives, there is no agreement on whether uses are methods, applications, or actions; therefore, there is no universal definition for BIM uses.

Although there is no universal definition, the definitions are aligned in that the BIM uses are present throughout the project lifecycle, as in each phase, it is possible to realize a specific benefit. The infrastructure lifecycle is defined as consisting of four phases: planning, design, construction, and operation [5, 6]. During all these phases, it is possible to apply various BIM uses according to the objectives that are established in the project, which increases the number of possible uses of this methodology [7]. The initial stages, namely, planning and design, are considered instrumental in the development of the project. According to MacLeamy's curve [8], the planning and design phases have a significant impact on the entire project; early efforts in these phases can help to prevent cost overruns and time delays at the construction site [9].

To realize the optimal applications of BIM, it is important to be aware of the BIM use level; in this way, it is possible to identify the possibility of improving the BIM in the project. However, it is possible to use a tool that enables the characterization of the BIM level but, not each BIM use in a project. Moreover, measuring the BIM level is not the same as measuring the BIM uses. These tools are BIM maturity models because several BIM maturity models facilitate understanding how companies apply the BIM methodology, where the term "BIM maturity" refers to the quality, repeatability, and degree of excellence within the BIM capability [10]. These maturity models can measure the BIM state but not specifically the application of BIM uses. Likewise, it is possible to evaluate the capacity at a specific time [11] in interorganizational project teams (specialists coming from different companies) [12], but it is not possible to evaluate the repeatability unless the client always works with the same project teams. Therefore, despite the existence of various BIM uses in the literature, there is no instrument to evaluate their level of implementation in construction projects.

Thus, addressing the lack of a tool to evaluate how BIM uses are applied in construction projects, this research proposes and validates a BIM Use Assessment (BUA) tool for characterizing the application levels of BIM uses in the planning and design phases of building projects. The objective assessment enabled by the BUA tool yields benefits for both the industry and the academia. Organizations can use this assessment to perform a self-diagnosis that supports strategic implementation of decisions and to qualify/select other organizations in the context of future projects or joint ventures. The academia, on the other hand, can use this assessment tool for industry benchmarking and diagnosis.

2. Research Methodology

The overall research methodology is organized into three stages: (1) identification, selection, and definition of BIM uses; (2) proposal of the BUA tool for characterizing the level of BIM use application; and (3) validation of the BUA tool. Figure 1 specifies the activities, research tools, and deliverables for each stage.

In the first stage, the user guides and manuals regarding BIM uses were identified to select the BIM uses to be evaluated in this research. The guides were classified according to three criteria: (1) definition of uses that are associated with an objective/application for the project, (2) classification of the uses according to the phases of the project life cycle, and (3) definition of uses that are supported by the scientific literature.

Subsequently, each use was defined based on the selected guide and a review of the literature from the last ten years. The search was carried out in the following libraries: Engineering Village, Web of Science, and Scopus. In this review, 64 references regarding the application of the BIM uses were identified in the design and planning phases of construction projects.

Next, a panel of experts validated the selection and definitions of the BIM uses. Table 1 lists the experts who participated in the three sessions. Finally, we created a definitive list of BIM uses and their definitions for the design and planning phases of construction projects.

In the second stage, the BUA tool is proposed for characterizing the levels of application of BIM uses in construction projects in the planning and design phases. A BIM use has various levels of complexity that are associated with its own characteristics, for example, the dimensionality of the model, the level of automation, and the number of associated systems. To establish each level, the researchers defined two or more characteristics for each use; those characteristics are elements that are associated with the objective or application of each BIM use. These characteristics were defined by analyzing the necessary factors for implementing each use successfully. Then, for each characteristic, a state was defined, which represents the level of complexity with which this characteristic is employed. Each characteristic and its state were defined in work sessions with the panel of experts.

Thereafter, combinations of states were defined according to characteristics that place a project in each level. Finally, the expert panel validated the combination of states that defined each level for each use. Therefore, in the BUA, evaluating each use on a scale from one to five is proposed, where the minimum level (1) does not use the BIM model and the maximum level (5) uses it in a way that realizes all its applications. The proposal of classification by levels allows having a structured and consistent tool. Table 2 presents a general description for each level; however, a detailed description of each level of each use is provided in the BUA (see Supplementary Data available here).

In the third stage, the BUA was validated by applying the proposed instrument to 25 construction projects in the planning and design phases. The only requirement for the evaluation is to declare that the company is using BIM. The evaluation process consisted of the following steps: First, a researcher conducted an interview with each BIM manager of each project. The interviews were conducted in a conversation-like manner to ensure that the interviewees would respond transparently [13]; this avoided the bias of previously having examined the answer for each level. Then, based on a recording of the interviews, two researchers

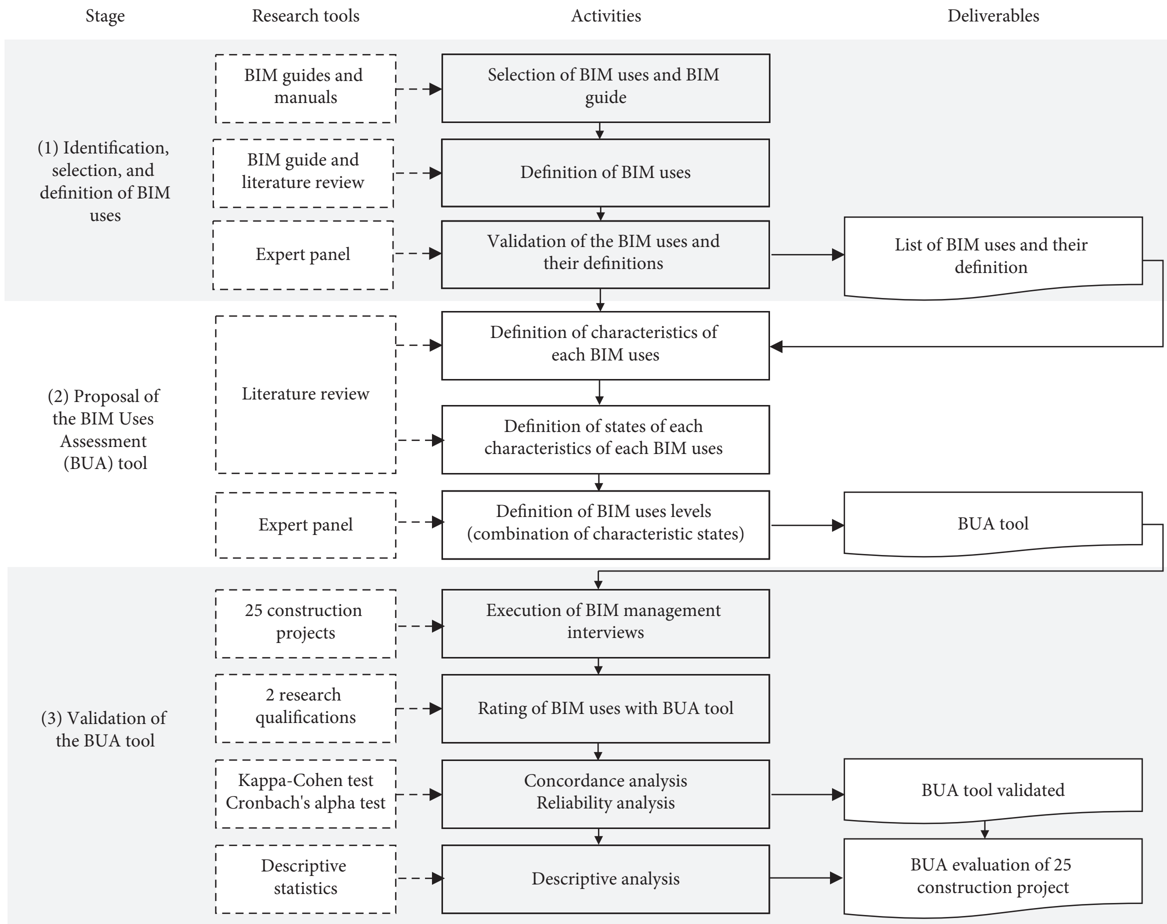


Figure 1: Research methodology.

Table 1: Characterization of expert panel.

Profession (grade)	Occupation	Field of work	Years of experience
Architect, Ph.D.	Professor and consultant	Construction management; virtual design and construction; building information modeling	>30
Civil Engineer, Ph.D.	Professor and consultant	Construction management; project management; lean construction; building information modeling	>30
Civil Engineer, Ph.D.	Professor and consultant	Construction management; virtual design and construction; building information modeling	>15
Civil Engineer, Ph.D.(c)	Professor and consultant	Construction management; lean construction; building information modeling	>10
Civil Engineer, M.Sc.	Researcher and consultant	Construction management; building information modeling	>5

Table 2: BIM levels—a general description for each level.

Level	General description
1	Traditional methods (2D model)
2	Low use of BIM and little information in the model
3	Medium use of BIM and sufficient information for BIM
4	High use of BIM
5	Full use of BIM; the best tools are utilized to realize all its applications

independently defined the level of the project for each BIM use. Next, in a collaborative session, the two researchers who qualified the projects were asked to discuss the final qualification of each use.

To validate the BUA tool, we conducted a concordance analysis of the evaluations of the two researchers and between each researcher and the final decision; we used the Kappa Cohen test to measure the level of concordance. Additionally, we conducted a reliability analysis of the BUA using Cronbach's alpha test to measure the level of internal consistency of the BUA tool.

Finally, a descriptive analysis of the results that were obtained for the 25 projects was conducted. Two measures, namely, central tendency and variability, for each of the uses were analysed. Via this approach, the uses with highest and lowest levels of implementation in the sample of this study were identified. The interviews were carried out by project and not by company because even if a company has several ongoing projects, the demands of the client or the nature of the project can affect the specifications of the application of BIM uses.

3. Identification, Selection, and Definition of BIM Uses

A BIM use is a set of actions and conditions that are associated with BIM, which together have a defined objective or application for the construction project. There are various guides or manuals that define BIM uses without specifying an objective/application or only as actions that are associated with the modeling process. Two examples are "existing condition modeling" and "record modeling," which are defined in the "BIM uses of Penn State" [2], because these uses are utilized for modeling without a defined application for the project. In applying a BIM use to a project, it is assumed that a BIM model exists. Other guides, such as "211 in model uses BIM" by Succar [3], consider additional modeling uses. In this guide, several modeling actions are specified, such as "fire modeling" and "foundation modeling." However, actions of this type are not considered BIM uses in this research.

To select a guide on which to base the definition of BIM uses, five guides or manuals were characterized based on three criteria: definition of uses, classification of uses, and literature background of uses (Table 3). The selected guide defined uses more in accordance with the definition that is proposed in this article, with a classification that is associated with the phases of the project's lifecycle, and with a more extensive literature background.

The BIM uses of Penn State were selected as the baseline guide in this research. This guide was selected for three main reasons: First, most BIM uses are aligned with an objective/application for the project, not just the modeling action. Other guides have BIM uses that are directly related to the modeling and not to the specified application; however, these are BIM tools, not BIM uses. Second, the classification of lifecycle phases is better suited to the requirements of this research. Third, every definition of BIM is strongly supported by the scientific literature.

Using this guide, an analysis was conducted on each of the uses that were specified in the planning and design phases of a construction project to determine which uses are considered in the evaluation tool. Fifteen uses are proposed in the planning and design phases by the Penn State guide; however, this research did not consider all the uses that are defined in the guide. The use "existing condition modeling" was deleted because it only considers the modeling and does not explain the associated benefit. In fact, the resulting model could be used, e.g., for cost estimation, 3D coordination, and site analysis. Moreover, "lighting analysis" and "energy analysis" are too specific in comparison with other uses; therefore, they were included in the use "sustainability analysis." Likewise, the uses "structural analysis" and "mechanical analysis" were included into the "engineering analysis" use, along with other uses such as "hydraulic analysis" and "fire protection system." Both changes were made in order to simplify the evaluation of BIM uses; however, it is possible that these simplifications are too general for specific projects where illumination, sound, or any specific analysis are carried out. Finally, ten of the fifteen uses were selected for the planning and design phases (Table 4).

Once the uses to be evaluated had been selected, the next step was to define each of them based on the Penn State guide and the analysed literature of 64 papers from the last ten years. Once the uses were defined, working sessions were held with the expert panel to provide feedback, implement the recommended corrections, and validate each of the definitions of the BIM uses.

4. Proposal of a BUA Tool for Measuring the Level of BIM Application

Once the BIM uses were defined, the characteristics, which are the actions or conditions that are necessary for applying these uses, are identified. Table 5 lists the characteristics that are used to assess each use. Additionally, each characteristic use is defined in annexed Supplementary Data available here (BUA).

Each characteristic is evaluated in various states; for example, in the use "space programming," the characteristic "distribution analysis" has the following states: manuals, consults, report, and automatic. A characteristic can be evaluated in one or more states since the states are not necessarily mutually exclusive. For example, in the use "site analysis" and the characteristic "type of model," the states are BIM and GIS; therefore, a project can have one or both. In the annexed Supplementary Data available here, all the states of each characteristic are presented.

To clearly illustrate the characteristics of the uses, the example below presents the selected features for the use "cost estimation." The "cost estimation" use has three main characteristics: the type of model, the origin of the quantities, and the number of systems on which the use is applied (Figure 2). The characteristics were defined by answering the following question: What yields a higher benefit on the application of this use? Via this approach, it will be possible to analyse the current state of a project and to identify the next steps for improvement. In this example, the use of BIM to support the cost estimation is at its maximum level of application when the extraction of quantities is bidirectional between the cost's software and the model, and based on a BIM model, without distinguishing if this is applied to a large or small number of specialties.

The characteristic "applied systems" is used to analyse the number of systems in which a BIM use is applied. The feature is divided into two options: "$<50\%$" and "$\geq 50\%$." In

Table 3: Characteristics of BIM use guides and manuals.

Guide or manual	BIM use definition associated with specific objective	Classification	Literature background
211 in Model Uses list [3]	General application of BIM	Type of information use	High
BIM uses Penn State [14]	With an objective or application for almost all uses	Lifecycle project	High
BIM Guidelines NYC [15]	General application of BIM	No classification	Medium
Singapore BIM Guide [16]	Without a specified objective or application	Lifecycle project	Low
BIM Procurement Guide Harvard [17]	General application of BIM	Lifecycle project	Medium

Table 4: Definitions of BIM uses for planning and design.

Stage	Use	Definition (proposal)	No. of papers
Planning, design	Cost estimation	A BIM model is used to generate accurate quantity takeoffs and cost estimates	7
Planning, design	Phase planning	A 4D BIM model is utilized to effectively plan, especially spatial planning, including spatial clashes and paths	9
Planning, design	Space programming	A BIM model is used to design and analyse the project's spaces and rooms and to assign to each space a use and its measurements	6
Planning, design	Site analysis	BIM/GIS is used to select and evaluate a site location and to select a building position on the site	8
Planning, design	Design authoring	A process in which 3D software is used to develop a building information model. A project is designed in a BIM model, where the typical iterations of a project are made, and everything is built directly in the BIM software	3
Planning, design	Design review	A process in which stakeholders interact with a BIM model and provide their feedback to validate multiple design aspects	5
Design	Engineering analysis	A BIM model and specialized software are used to conduct an engineering analysis to identify the most efficient method or design	4
Design	Sustainability evaluation	A process in which the sustainability of a facility is evaluated and tracked using a sustainability metric system	8
Design	Code validation	A process in which code validation software is utilized to check the model parameters against project-specific design or construction codes or norms	7
Design	3D coordination	A process in which 3D coordination software is used to identify 3D geometric conflicts by comparing 3D models of building systems	7

Table 5: Uses and their characteristics.

Phase	BIM use	Characteristics
Planning	Cost estimation	Source of quantities, type of model, and applied systems
	Phase planning	4D model, type of use, and link type
	Site analysis	Type of model and type of analysis
	Space programming	Type of model and distribution analysis
Design	Design review	Type of model, immersive lab, and list of requirements
	Code validation	Type of software, type of model, applied systems, and level of mock-up
	Sustainability analysis	Type of model, type of software, and applied systems
	Engineering analysis	Type of model, compatible software, applied systems, and documentation
	Design authoring	Type of models, generative models, and applied systems
	3D coordination	Type of models, analysis method, and applied systems

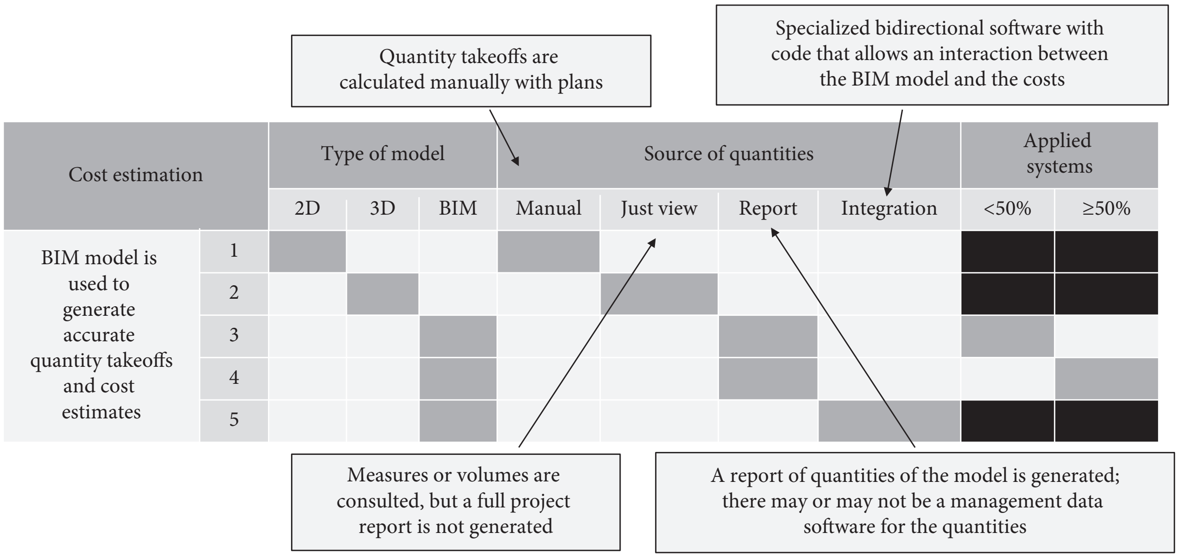


Figure 2: BUA—cost estimation.

Figure 2, the feature "applied systems" corresponds to the two last columns; however, the number of systems depends on the characteristics of the project; hence, the tool cannot use a fixed number for each of the options. Therefore, it is necessary to calculate the number of systems to which a BIM use can be applied.

Once the levels have been defined, a BUA is constructed as a template for each use, which includes the use name, use definition, use levels (1 to 5), and use characteristics (Figure 2). This BUA tool serves as a rubric and should be read horizontally. The light-grey squares indicate the conditions that must be satisfied to belong to a level. Likewise, the dark-grey squares indicate the possibilities within a level. The dark-grey colour is applied with the objective of avoiding subjectivity to enable the analysis of various combinations at the same level. For example, a project is assigned a score of one for the "cost estimation" use if it uses a 2D model to calculate manually the quantities for over or under the 50% of the systems.

5. Validation of the BUA Tool via the Evaluation of Projects in the Planning and Design Phases

To validate the consistency resulting from the application of the proposed BUA tool, 25 civil infrastructure and building construction projects were considered, which were all in the first phases of the lifecycle (planning and design) (Table 6).

To evaluate each project, interviews were conducted with the BIM manager and/or project manager. All the interviews were recorded with the interviewees' consent so that their answers could be later analysed by two BIM researchers, who independently evaluated each use of the BUA.

Finally, the evaluators held a meeting to decide on the final score of the project for each use; they focused on the categories in which the scores differed between the two evaluators. In conducting this evaluation, the evaluators followed the format that is shown in Figure 3. The template must be filled by a BIM specialist who has been selected through an interview with the project leaders.

To validate the BUA tool, three concordance analyses were performed: (i) between the answers of the two researchers, (ii) between the answers of Researcher 1 and the final decision for each use, and (iii) between the answers of Researcher 2 and the final decision for each use. Cohen's Kappa was applied to each of these scenarios (Table 7), and an almost perfect level of agreement of over 93% was reached in all three cases [15]; hence, the tool is unbiased and precise.

Then, as the next step in validating the BUA tool, the internal consistency of the measuring scale was analysed using Cronbach's alpha coefficient. For the BUAs of 10 items and 25 test projects, a Cronbach's alpha coefficient of 0.8617 was calculated. Hence, the elements of the BUA tool assess the same characteristic for a project for each BIM use. From the high level of internal consistency (reliability) and the high level of agreement between the interviewers, it is concluded that the BUA is an objective and consistent tool for evaluating the levels of BIM uses in the design and planning phases of construction projects.

Based on the high measurement performance of the tool in the validation process, the BUA tool can systematically characterize the levels of application of the BIM uses in the planning and design phases of building projects. Thus, the proved trustiness of this tool to assess BIM uses in the early stages of the project enables self-diagnosis of an organization's practices regarding how BIM is used in their projects. For example, an organization can understand that its cost estimation process (BIM use) consists of consulting quantities from 3D models in less than half of their main cost items, while its design review process (BIM use) is based on a nonimmersive visualization of BIM models with an informal identification of design issues. This understanding can allow a company to formulate an improvement plan to take full advantage of BIM for its projects. Additionally, a company can use the BUA tool to assess the BIM use of potential

Table 6: Summary of project characteristics.

Country	Project	Total	Public	Private	External clients	Internal clients
Chile	Building	7	0	7	3	4
	Infrastructure	2	2	0	2	0
Colombia	Building	11	0	11	5	6
	Infrastructure	1	1	0	1	0
Spain	Building	3	0	3	3	0
	Infrastructure	1	0	1	1	0
Total		25	3	22	15	10

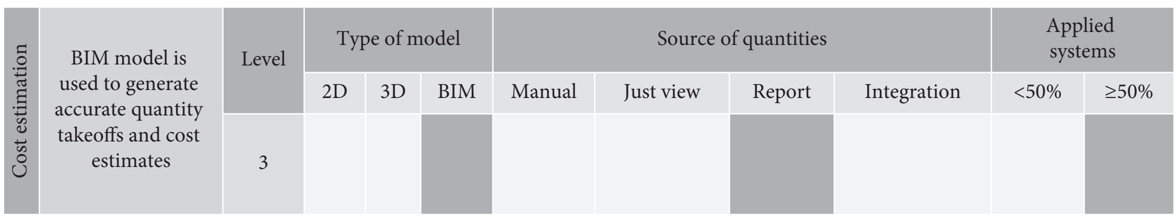


Figure 3: Cost estimation evaluations (example of an assessment).

Table 7: Concordance analysis.

	Researcher 1–Researcher 2	Researcher 1–final decision	Researcher 2–final decision
Agreement percentage	93.7	96.8	96.8
Kappa	0.91	0.96	0.95
p value	0.02	0.01	0.01

partners or design consultants in future projects where certain BIM uses are required. Additionally, the results of the assessment done with the BUA tool in a particular project can be compared to successful cases of BIM application within the company or the industry (if available) to identify the most efficient practices for BIM uses.

Using the 25 evaluated test projects, a descriptive analysis was conducted to determine the distribution of the levels for each BIM use. Figure 4 shows a box plot for each BIM use. According to this figure, the BIM use with the highest level of application is "3D Coordination" and the BIM use with the lowest level of application is "Phase Planning," which is associated with Level 1 in almost all cases (three projects showed an application, which were represented as atypical dots and asterisks). This low application of "phase planning" is due, according to the interviewees, to the lack of a specific requirement for this use in the contract. "Sustainability Analysis" was another BIM use that has application level of 1; however, it has higher variability. For this BIM use, even if not all the projects required an environmental certification by the clients, some projects had their own environmental requirements to be satisfied, for which BIM was helpful.

BIM uses "Site Analysis," "Space Programming," and "Code Validation" were associated with Level 2 of application, while "Design Review" and "Engineering Analysis" were associated with Level 3. Regarding "Engineering Analysis," according to the interviewees, it is difficult to ask the external designers to develop the whole process in BIM software.

Finally, 6 out of the 10 evaluated BIM uses presented high variability in terms of the application levels. This is due to the differences among the projects in terms of their characteristics, the companies that execute them, and their clients. For most of the projects, an improvement opportunity was identified in the BIM uses.

Additionally, hypothesis tests were conducted to identify significant differences according to the characteristics of the evaluated projects. Nonparametric hypothetical tests were applied with a significance level of 95% since the variable of each evaluation is ordinal qualitative. The Mann–Whitney U test was used to compare pairs of samples, and the Kruskal–Wallis test was used to compare three samples. No significant differences were identified between projects with a public or private client. There are also no significant differences between projects with an internal or external client. There are no significant differences between infrastructure projects and building projects. Differences were identified in terms of the countries of origin of the projects; p values of less than 0.05 were obtained between the pair Chile-Colombia and Spain, where in the latter country, the projects had significantly lower evaluations. No significant differences were identified between the projects in Chile and Colombia.

Therefore, from this initial evaluation, it can be noted that there is a high variability in the types of BIM uses in the design planning phases, where the most developed use is coordination between specialties, and the least developed is 4D planning. In addition, this sample shows high variability in the level of development and automation of each use, for example, in cost estimation or design authoring.

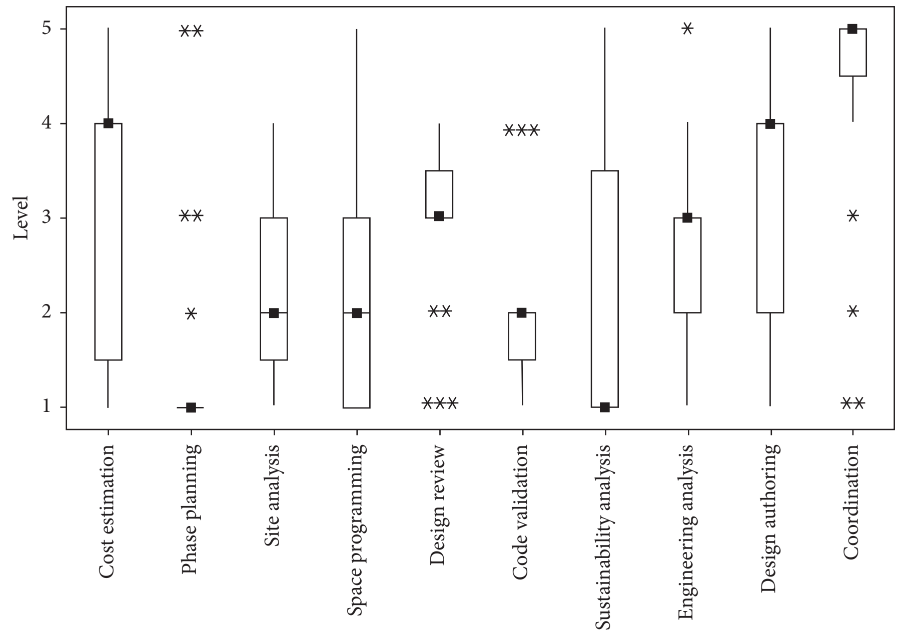


Figure 4: BIM use application levels.

6. Conclusions

The proposed BUA tool that is presented in this study contributes to the diagnosis of the application of BIM uses, thereby enabling companies and clients to identify the BIM use state of the project, the way in which the BIM uses are being implemented and opportunities for improvement. Via this approach, it is possible to realize higher benefits from the BIM methodologies when they are applied in the earliest stages of the projects. Since countries are encouraging the use of BIM methodologies, having a tool that enables the assessment of the application of BIM uses in projects is advantageous for those who are in the process of implementing or are seeking to implement this methodology efficiently. Then, the BUA tool becomes crucial for companies in evaluating how they are utilizing all the "uses" that BIM can offer. Likewise, BUA tool can be used to evaluate companies to be contracted seeking for the specific BIM use level, or also for benchmarking the BIM use level in the industry.

In the validation process of the BUA tool, a high consistency value was obtained; i.e., the tool is reliable and measures what is being measured. In addition, when the same project was evaluated by two researchers, a high percentage of agreement was obtained; therefore, it can be concluded that the tool is free from the evaluator's bias. The BUA tool has high concordance and consistency values; however, it is recommended that external specialists evaluate a project to eliminate biases. The BUA can be used as a self-assessment tool if the examiner is knowledgeable regarding BIM. In addition, this evaluation enables the comparison between projects of the same company or of different companies and promotes benchmarking and continuous improvement in organizations.

The descriptive analysis and hypothesis tests were conducted with the pilot test of 25 projects. The use of a larger sample size is recommended for obtaining more general conclusions according to the characteristics of the project. The BUA defines each level as a combinatorial of states associated with each characteristic of each use; however, this combinatorial could be different. The uses "sustainability analysis" and "engineering analysis" group several specialties, respectively; this simplification could generate an information gap if the objective of the assessment is to understand the use of each specialty individually.

Future work will focus on the extension of BUA, which was developed for implementation in the planning and design phases, to the other project lifecycle phases, namely, the construction and operation phases. In addition, it would be of substantial value to assess the level of socialization of each BIM use since, for effectively using BIM, the integration of information among all factors of the project is necessary. This would involve assessing the way in which the information is managed, shared, and stored. Additionally, with a greater number of projects, a deeper descriptive analysis can be made of the states in which each characteristic of each BIM use is located.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by FONDECYT (1181648 to Alarcón L. F. and Mourgues C.) and CONICYT, Chile

(PCHA/National Doctorate/2018-21180884 to Herrera R. F.).

Supplementary Materials

The BUA is composed of three sheets in an Excel file. The first two sheets ("Plan" and "Design") define the conditions for belonging to each level for the BIM uses and are similar to help tables. The third sheet, namely, "Interview Template," should be used to conduct the interview. In this template, the project data are obtained by writing an "*x*" in the corresponding box and using the first sheet, the level of implementation for each BIM use in the project can be identified. (*Supplementary Materials*)

References

[1] National Building Specification (NBS), *National BIM Report 2018*, National Building Specification, Newcastle, UK, 2018.

[2] R. G. Kreider and J. I. Messner, *The Uses of BIM: Classifying and Selecting BIM Uses*, Penn State, State College, PA, USA, 2013.

[3] B. Succar, *211 in Model Uses List*, 2016, https://bimexcellence.org/files/211in-Model-Uses-Table.pdf.

[4] D. Bloomberg, D. Bloomberg, M. R. Burney, and D. J. Resnick, *BIM Guidelines NY*, Department of Design Construction, New York city, NY, USA, 2012.

[5] S. Azhar, "Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry," *Leadership and Management in Engineering*, vol. 11, no. 3, pp. 241–252, 2011.

[6] K. Eastman, C. M. Teicholz, P. Sacks, and R. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley & Sons Ltd., Hoboken, NJ, USA, 2nd edition, 2011.

[7] K. Hannele, M. Reijo, M. Tarja, P. Sami, K. Jenni, and R. Teija, "Expanding uses of building information modeling in life-cycle construction projects," *Work*, vol. 41, no. 1, pp. 114–119, 2012.

[8] The American Institute of Architects, *Integrated Project Delivery: A Guide*, The American Institute of Architects, Washington, DC, USA, 2007.

[9] S. Talebi, "Exploring advantages and challenges of adaptation and implementation of BIM in project life cycle," in *Proceedings of the 2nd BIM International Conference on Challenges to Overcome*, pp. 1–20, BIMForum Portugal, Lisbon, Portugal, October 2014.

[10] B. Succar, W. Sher, A. Williams, B. Succar, W. Sher, and A. Williams, "Measuring BIM performance: five metrics," *Architectural Engineering and Design Management*, vol. 8, no. 2, pp. 120–142, 2012.

[11] C. Wu, B. Xu, C. Mao, and X. Li, "Overview of BIM maturity measurement tools," *Journal of Information Technology in Construction*, vol. 22, no. 3, pp. 34–62, 2017.

[12] J. Sydow and T. Braun, "Projects as temporary organizations: an agenda for further theorizing the interorganizational dimension," *International Journal of Project Management*, vol. 36, no. 1, pp. 4–11, 2018.

[13] D. W. Turner, "Qualitative interview design : a practical guide for novice investigators," *The Qualitative Report*, vol. 15, no. 3, pp. 754–760, 2010.

[14] R. Kreider, *An Ontology of the Uses of Building Information Modeling*, Pennsylvania State University, State College, PA, USA, 2013.

[15] M. L. McHugh, "Interrater reliability: the kappa statistic," *Biochemia Medica*, vol. 22, no. 3, pp. 276–282, 2012.

[16] Building and Construction Authority, *Singapore BIM Guide—V2.0*, Building and Construction Authority, Singapore, 2013.

[17] Harvard University Construction Management Council, *BIM Uses Guide*, Harvard University Construction Management Council, Cambridge, MA, USA, 2010.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 4163625, 18 pages
https://doi.org/10.1155/2019/4163625

Research Article

BIM-Based Digital Fabrication Process for a Free-Form Building Project in South Korea

Joo-sung Lee,[1] Nahyun Kwon,[1] Nam-hyuk Ham,[2] Jae-jun Kim,[3] and Yong-han Ahn[1]

[1]*Department of Architectural Engineering, Hanyang University, 55 Hanyangdaehak-ro, Sangrok-gu, Ansan-si, Gyeonggi-do 15588, Republic of Korea*
[2]*Department of Digital Architectural and Urban Engineering, Hanyang Cyber University, 220, Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[3]*Department of Architectural Engineering, Hanyang University, 220, Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*

Correspondence should be addressed to Nam-hyuk Ham; nhham@hycu.ac.kr

Received 30 November 2018; Revised 16 February 2019; Accepted 11 March 2019; Published 23 May 2019

Academic Editor: Mohammad R. Hosseini

Since the concept of building information modeling (BIM) was introduced in South Korea in 2008, digital fabrication concerning free-form shapes and complex parametric information has been expanding owing to the development of BIM software and tools. However, the digital fabrication process is inadequate in terms of efficiency and productivity because of the need to convert from conventional two-dimensional (2D) drawings to a BIM design; this adversely affects the unified design, fabrication, installation, and inspection processes. Moreover, an optimized process has not been developed thus far because the productivity of digital fabrication has not been quantitatively verified for various projects in the field. This study proposes a BIM-based digital fabrication process for prefabricated parts of buildings. In addition, a productivity analysis method based on the queuing model is proposed using personnel input and performance calculation data to verify productivity. It is expected that the digital fabrication process and productivity analysis model proposed here will be applied to complex digital fabrication works.

1. Introduction

The main trend of the construction industry in the 21st century is the creation of different spaces to improve the quality of human life and in forms that were previously unavailable to meet various user needs [1]. These needs have increasingly decided that the buildings be massive and the shapes be more complex; thus, the design of free-form and complex elements, manufacture of building components, and construction technology at the site must be supported to meet these needs [2]. Existing architectural techniques and paradigms are mostly available only in fragments, such as the optimal design technology for complex structures, techniques for fabrication of components, and precise installation technology. Therefore, the cost and time requirements for design, fabrication, and construction of complex types of structures will increase, eventually leading to construction errors and deterioration of building quality [3]. However, since the BIM concept was introduced in Korea in 2008, efforts have been made to overcome the problem of productivity degradation in the life cycles of construction projects [4].

Building information modeling (BIM) technology has been rapidly replacing conventional construction models, such as two-dimensional computer-aided design (2D CAD), paper documents, and Excel chart-based schedules, by improving the technical level of construction automation, introducing BIM-based innovations, and application of integrated project delivery (IPD) method in several countries. Digital fabrication is one such technology developed through the application of BIM and virtual design and construction (VDC) methods in the construction industry. Through BIM-based digital fabrication, designers, builders, and manufacturers of construction materials can perform detailed design and examination of the products to be fabricated as digital objects [5, 6].

BIM can integrate design, manufacturing, and construction processes to increase the level of transparency and interoperability among partners in construction projects that use prefabricated components [7]. Based on this advantage, BIM-based digital fabrication technology simplifies the procurement process in construction and improves the productivity of the workflow between designers, builders, and those involved in the manufacturing of construction components [8]. Moreover, from a fabrication productivity perspective, construction member manufacturers can utilize the data input from BIM objects to assist the fabrication process, and these are parametric data that are not provided by conventional 2D-based fabrication methods [8]. Automatic member shape recognition and fabrication are possible by inputting parametric BIM fabrication data into the member production process of the computerized numerical control (CNC) machine.

Despite this advantage, the digital fabrication process remains very inefficient in South Korea. In particular, although the level of digital fabrication requirement is very high for free-form buildings because each material has its own free-form shape, development of the elementary technologies required for actual fabrication and construction has been slow. Owing to these technical limitations, optimized processes or management methodologies for the life cycle management of free-form construction members, including design, fabrication, installation, and construction, are not sufficient, despite the rising demand for free-form buildings in South Korea. This affects the cost, construction period, and quality of projects.

Therefore, this study aimed to establish the life cycle process, including design, fabrication, and construction, of free-form structural members that are components of free-form buildings. Moreover, the proposed digital fabrication process for free-form construction members was implemented in an actual building based on a case study, which allowed for technical verification and productivity evaluation, as well as verification of the productivity of the implemented process.

2. Literature Review

2.1. Prefabrication of Construction Project. The prefabrication method in the construction industry is a way to reduce the overall project schedule since the processes at the factory and the on-site fields are carried out simultaneously. This advantage can be obtained by simultaneously running a large number of processes on-site and at the factory, compared to the on-site process, in which all tasks are performed in order [9]. This enables the contractor to actively utilize the prefabrication method for projects with an extremely short site schedule and complicated processes [9]. Prefabrication also helps to reduce costs by preventing the waste of materials due to poor field processing and through the repeated training of workers [10, 11]. In addition, previous studies found that the use of prefabrication methodologies improved the quality of construction. Digital applications and IT technologies can significantly improve the quality of construction by accurately reflecting the initial design and entering this design in the fabrication equipment [12–15]. In addition, prefabrication has the effect of reducing the wastage of resources by reducing the warehousing space, improving material quality, and optimizing the supply chain [7].

2.2. Digital Fabrication. Digital fabrication refers to a methodology that systematically manages all processes, such as generation, design, material processing, and construction of a structure that is intended to be produced by utilizing digital tools [16]. Digital fabrication technology is primarily used in specific projects, such as free-form buildings. In such projects, fabrication processes that exceed the conventional construction production methods are created through design goals and technical innovations [17]. The digital fabrication process of a construction project is generally classified as additional fabrication, and it is based on computer-based design methods and robotic-based production processes [18]. In particular, for the construction of free-form parts, various members are processed and assembled through additional fabrication processes that utilize industrial robots [19]. Owing to the recent development of digital technologies and the introduction of computer-based fabrication, buildings with very complex designs can also be realized [20].

2.3. Implementation Cases and Benefits of BIM-Based Digital Fabrication. A representative case of the use of digital technology for implementing digital fabrication is BIM. However, the application of BIM is determined by the characteristics of the project and can be limited to simple conversions of 2D CAD into a three-dimensional (3D) model or it can be more complex as in an ideal case in which design, fabrication, and construction are integrated and maintenance is considered [21]. Won et al. [22] conducted a case study on a collaborative organization and information management method based on a free-form project. Frank Gehry first applied CATIA, a design software program primarily used for the design of airplanes or automobiles, to construction in the Fish project (1991-1992) and aggressively utilized it for the 3D representation of curved shapes and the production process of construction members. Moreover, from the perspective of project information management, assembling one integrated team with designers and constructors for the 3D model constructed through CATIA improved the completeness of the design and contributed to the manufacturing of components and on-site construction. In particular, in the Bilbao Guggenheim Museum project (1991–1997), approximately 50,000 2D drawings were automatically created using a 3D model and were provided to the project participants.

Jang and Lee [23] analyzed the effect of applying multitrade prefabrication, in which multitrade mechanical, electrical, and plumbing (MEP) elements were preassembled in a factory, for construction instead of using the existing prefabrication method applied to a single process, and they also analyzed the technical requirements for this. Skanska USA reported that productivity increased by approximately 300%, and the construction period was reduced by eight weeks in the Miami Valley hospital project by applying multitrade prefabrication to the corridor rack and bathroom pods [24]. Mortenson [25] reported that the total construction period was reduced by approximately 15%, but the construction cost increased by approximately 6% through the application of multitrade prefabrication in the Saint Joseph Heritage project.

2.4. Limitations of Existing Research on Digital Fabrication. Despite the abovementioned advantages of digital fabrication, few studies on productivity factors, such as reduction of schedules, quality, and resource reduction during the manufacturing and construction stages, have been conducted. This is because the definition or efficiency of the digital fabrication life cycle process has never been verified, despite interest in implementing building element technology using digital fabrication [26]. In addition, the limitations of contracts, participants, organizations, and technologies hinder the unification and utilization of BIM data in digital fabrication, and as a result, the efficiency of BIM utilization is extremely low [27]. This is essentially owing to the absence of a methodology and technical limitations for managing processes based on BIM data throughout the fabrication life cycle [28].

2.5. Research on the Productivity of Digital Fabrication. Numerous studies have been conducted to measure the benefits of the BIM-based digital fabrication work process mentioned in Section 2.2, i.e., cost, construction period, and quality.

Jang and Lee [29] conducted a case study on the multitrade corridor rack prefabrication case project. They proposed a prefabrication process for the corridor MEP rack and analyzed its effectiveness using details of the process, productivity, and economic efficiency. de Soto et al. [30] proposed a new methodology for the automatic production of complex concrete walls in the field. They found that the process of the wall work changed when a concrete pouring robot was used and verified the effects of the CYCLONE discrete event simulation system on the cost and time to validate the process. Fazel and Izadi [31] proposed a work methodology for a free-form modular surface using a head-mounted display visualizing an augmented reality for accuracy and construction period reduction of masonry work and verified the quality of the augmented-reality-based HMD methodology based on the visualized augmented reality coordinates and the coordinates of the actual masonry. Hamid et al. [8] proposed a CNC machine utilization methodology using a BIM-based digital fabrication model for woodwork. In particular, they proposed a CNC utilization methodology using a three-step cycle including process-level knowledge, component-level knowledge, and object development and validated the methodology through component fabrication. Knippers [32] redefined the role of the architect and proposed a new process for digital fabrication and analyzed a case that reflected these proposals. Li et al. [33] proposed a prefabrication production process for housing (RBL-PHP) using the RFID, BIM, and Lean methods and performed a simulation composed of steps, such as the prefabricated production of the structure, constraint identification, standardized work, and RBIMP, to verify the proposed process. Nahangi and Haas [34] proposed a three-step model (preprocessing, registration, and condition assessment) for 3D quality examination to perform quality and compliance verifications in the prefabrication phase of building piping. Wang et al. [35] classified the BIM-based framework for a unified process of the design-construction phases for the MEP system layout into the design, fabrication, and construction phases. Said [36] proposed a prefabrication applicability review model of electrical work.

The previous studies did not present a process for the entire life cycle, including basic design, shop design, prefabrication, and installation. The effects of the methods proposed in these studies were verified through case analysis, statistical analysis, and simulations.

2.6. Queuing Model. The queuing theory has been used in different research areas. Queuing systems are expressed using several types of queuing models [37]. Customers arrive at a queuing system individually and randomly to receive services. If a customer cannot receive services immediately upon arrival, the customer waits in a queue. Normally, one or more servers provide services. Each customer receives services from one of the servers and leaves the system. The queuing theory can be utilized to efficiently analyze the workflow, which is a network of various activities [38]. In the queuing system, the times between the arrivals of customers are referred to as the interarrival times. When sufficient data on the arrival of customers are collected, the average number of arriving customers per unit time can be estimated. Unlike conventional performance measurement tools, the performance and effectiveness measurement method based on the queuing model can measure the work of service providers at the request of customers based on time and manpower. It is, therefore, possible to measure practical work productivity. Ham and Kim [39] analyzed the performance of BIM personnel who stayed on the construction site for the construction phase of a BIM application project. They focused on the requests for information (RFIs) of the project participants considering the characteristics of the queuing model. Kim et al. [40] found that costs may occur owing to the waiting times of the project participants depending on the performance of the BIM personnel.

Many studies have indicated that the queuing model is an optimized tool for analyzing the performance of a construction process and output. Queue performance measures, such as waiting time and queue length, are some of the most important simulation outputs in construction management for analyzing the balance between different resources [41]. Furthermore, queue performance measures can make the estimation of important outputs of the construction performance simulation reliable as they use appropriate quantitative modeling of activity duration and input resources [41]. Queue performance measures, such as average queue length and waiting time, are important for finding bottlenecks and optimizing the amount of resources for construction projects [42]. The digital fabrication process is nonquantitative, and it deals with different types of factors, and thus, performance simulation using the queuing model is an optimized methodology for investigating the productivity and efficiency of processes [30].

3. Research Methodology

3.1. Research Approach: Exploratory Case Study. In this study, a digital fabrication process formulated through case analyses and an evaluation method based on the queuing model that is capable of analyzing the construction process is proposed. According to Gerring [43], case analysis is "an intensive study of a single unit for the purpose of understanding a larger class of (similar) units." From a general perspective, case analysis is typically a research methodology that enables empirical and plentiful explanations and analysis of one phenomenon occurring in a specific case based on the diversity of data sources [44]. Therefore, a law, as a theoretical proposition and logical configuration, can be defined through the evidence derived from a case, and the methodology can be used for quantitative and qualitative evidence collection [45, 46].

This paper comprises a literature review, proposal of digital fabrication process for a free-form podium, case analysis, and productivity analysis for the proposed digital fabrication process, as shown in Figure 1.

3.2. Implemented Case: S Tower at South Korea. S Tower is located in Seoul, South Korea. It is a very tall building with 123 floors and a height of 555 m. It was designed by K&B Architects and constructed by L E&C. L CM company performed the CM. Digital fabrication was applied to the podium region (approximately 8,200 m^2) of the S Tower.

A CNC T-BAR shape control system was selected for the precise shape control of the podium region with a free form. The CNC T-BAR shape control system applied the member concept of a section shape, which is used for producing the curved structures of airplanes and ships, to construction projects [47]. This system precisely controls all the coordinate points of a curved surface with vertical and horizontal variable thickness attributes. After developing the cross section formed by cutting a free-form curved surface into a curved shape, the system processes a steel plate with CNC equipment (e.g., laser, router, and plasma). The system performs the mass production (or fabrication) of the flange, web, and connecting members of vertical and horizontal T-bars with various curvatures.

4. Digital Fabrication Process for Free-Form Podium

4.1. Digital Fabrication Process Proposal. The case analyzed in this study was the free-form paneling and subwork installed in the podium region of the S Tower. The process for performing digital fabrication was developed in the planning phase.

During on-site construction, the traditional construction method, prefabrication is not performed, and direct on-site installation is performed. This causes many problems, such as quality degradation, cost increase, weather and ambient air impacts, and inconvenient work site conditions caused by construction period delays and quantity increases. As such problems largely occur with free forms, complex shapes, and multitrade objects, design or construction is generally difficult. Prefabrication is considered for these parts, and the digital fabrication method can be applied to achieve the prefabrication of free-form or complex structures. Therefore, while the conventional construction method is a simpler design-construction method, prefabrication is added to the construction processes, including the manufacturing work.

The case studied herein was part of a free-form panel fabrication. In particular, it involves significant difficulties, such as the derivation of a design reflecting 100% of the designer's intention for the free-form panel with a secondary curved surface; selection of an appropriate structural system for supporting the design; derivation of drawings with numerical data, such as accurate coordinates, from the design; creation of shop documents for panel fabrication based on the basic design; shop model creation and utilization for CNC machine utilization; on-site construction consistent with the drawings; precise quality control for fabrication and construction; and measurement of the accuracy improvement.

To overcome the difficulties of digital fabrication, a BIM-based model capable of implementing the accurate shape as intended and an implementation process that utilizes the unified data based on the BIM model must be used. In particular, an optimized work plan that accounts for the personnel and the construction period of each task involved in the digital fabrication task during the project life cycle, including design, fabrication, on-site delivery, and installation, is required. As shown in Figure 2, a digital fabrication process was developed to overcome various difficulties expected in the case project.

4.2. Case Application of the Digital Fabrication Process

4.2.1. Step 1: Design of Free-Form Part Shape and Panels. When a podium is designed in the design phase, a detailed construction method is not typically considered. Therefore, the design model as shown in Figure 3 does not include specific information for construction.

However, in the construction phase, the constructability, economic efficiency, and quality must be considered. Digital fabrication for the podium region was performed for seven months, including fabrication design, member fabrication, and construction. In the fabrication design phase, the model was optimized by dividing the exterior panel of the free-form region into panels composed of curved surfaces in two directions, flat panels and curved surface-plane connection panels, as presented in Table 1.

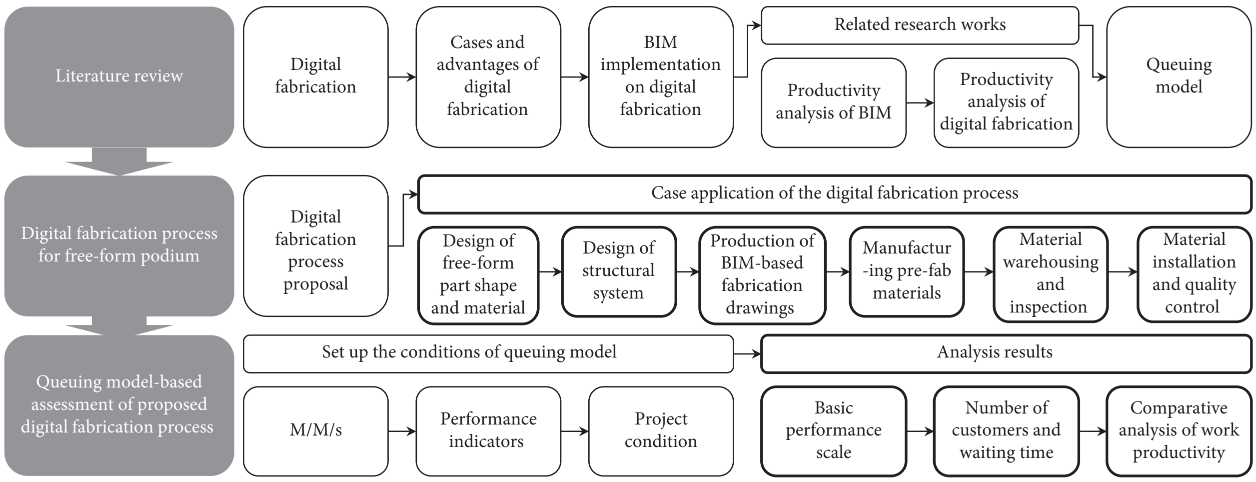


Figure 1: Research process.

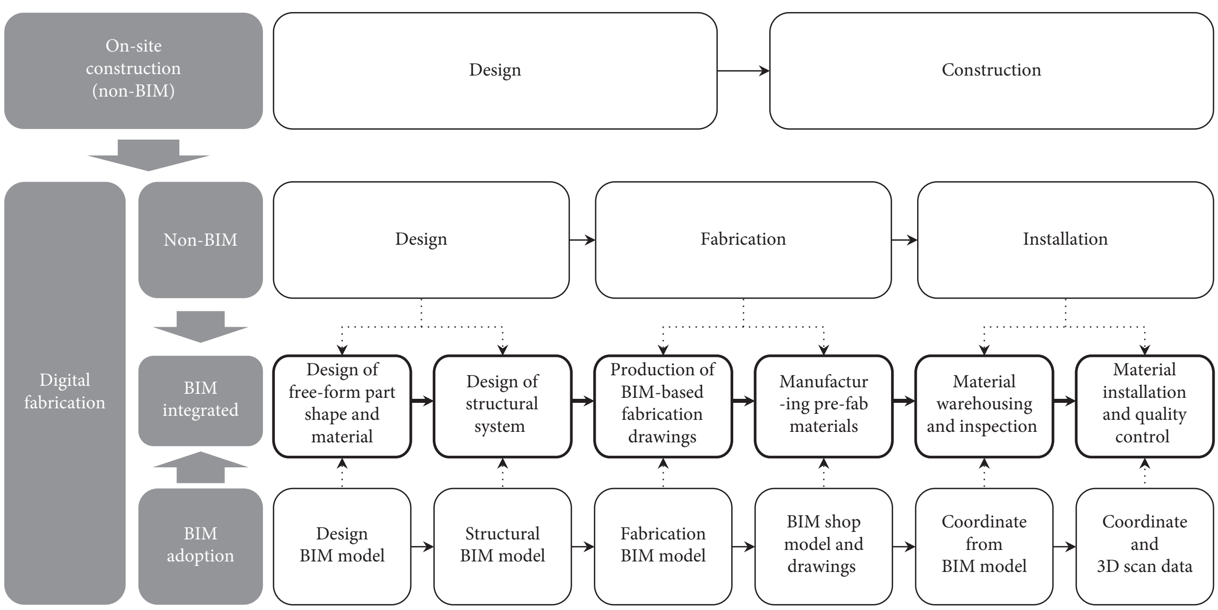
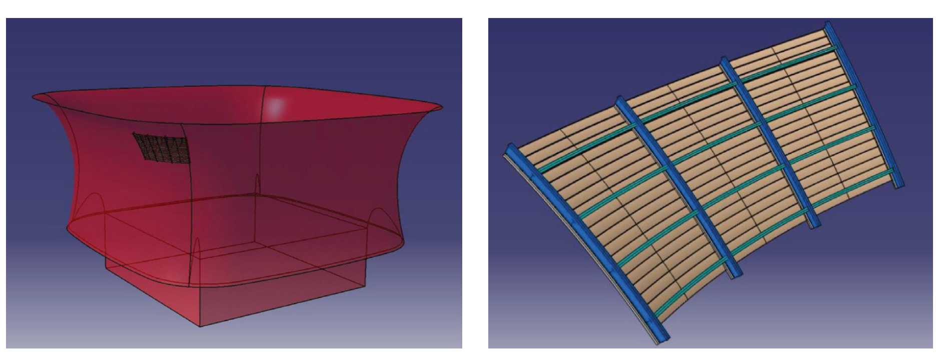


Figure 2: Proposed digital fabrication process.



(a) (b)

Figure 3: Design model: (a) preliminary concept model and (b) DD stage design model.

Table 1: Panel optimization of upper and lower surfaces.

Category	Upper surface	Lower surface
Two-way irregular panels	1,867 m^2	240 m^2
Flat and irregular panels	465 m^2	73 m^2
One-way irregular panels	2,555 m^2	1,688 m^2
Optimization area (% of gross area)	2,332 m^2 (approx. 48%)	313 m^2 (approx. 16%)

This is the basic repetition procedure for a production process used to construct a large number of panels and maximize quality and productivity. Figure 4 shows the shape optimization model of the podium region. This becomes the reference surface of the final materials, such as the NT panels and reveal. Moreover, through this reference surface, the structural members and accessories for controlling the shapes of the final materials are precisely fabricated.

4.2.2. Step 2: Design of the Structural System Controlling the Panel Shape. The coordinates for the free-form curved surface of the NT panel were controlled by the CNC T-BAR shape control system. First, the secondary structure attached to the primary structure was designed, as shown in Figure 5. The primary structure was designed and engineered based on the free-form curved surface shape from Step 1. This history is utilized for producing fabrication drawings, and it provides detailed processing information (e.g., bending and bolt and nut positions) for factory fabrication. Moreover, to remove the clashes between the structural system and MEP materials, the BIM-based clash detection step was performed using the Autodesk Navisworks manager, as shown in Figure 6.

Based on the secondary structure, vertical and horizontal CNC T-BAR shapes for controlling the free-form curved surface shape of the NT panel were designed, as shown in Figure 7. Moreover, the details of the CNC form plate for controlling the position of the NT panel along with the reveal and NT panel, which are finishing materials, were examined. The NT panel, a finishing material, and the CNC form plate, a structural member, were connected, and the details of the adjustment bracket for precisely controlling the shape were examined.

An integrated fabrication model with the construction method and details for precisely controlling the free-form curved surface shape was completed, as shown in Figure 8.

4.2.3. Step 3: Production of BIM-Based Fabrication Drawings. The fabrication model for which the construction method and details were examined was utilized to produce drawings for factory fabrication. Table 2 lists the members fabricated in factories for this case project. The total quantity of the members was 29,654. When the adjustment brackets and small members were included, 35,000 or more members needed to be produced.

Digital fabrication companies provided fabrication drawings and quality criteria (e.g., welding and bolt/nut fastening methods) to the companies responsible for the fabrication and construction of each member using the fabrication model. As the members were produced by different companies, the fabrication drawings for factory fabrication, such as the planar figure, were transmitted according to the classification of the member set unit (e.g., the CNC T-BAR and reveal) as shown in Figure 9. The detailed drawings for fabrication of the CNC T-BAR and secondary steel structure were extracted from the fabrication BIM model, as shown in Figure 10.

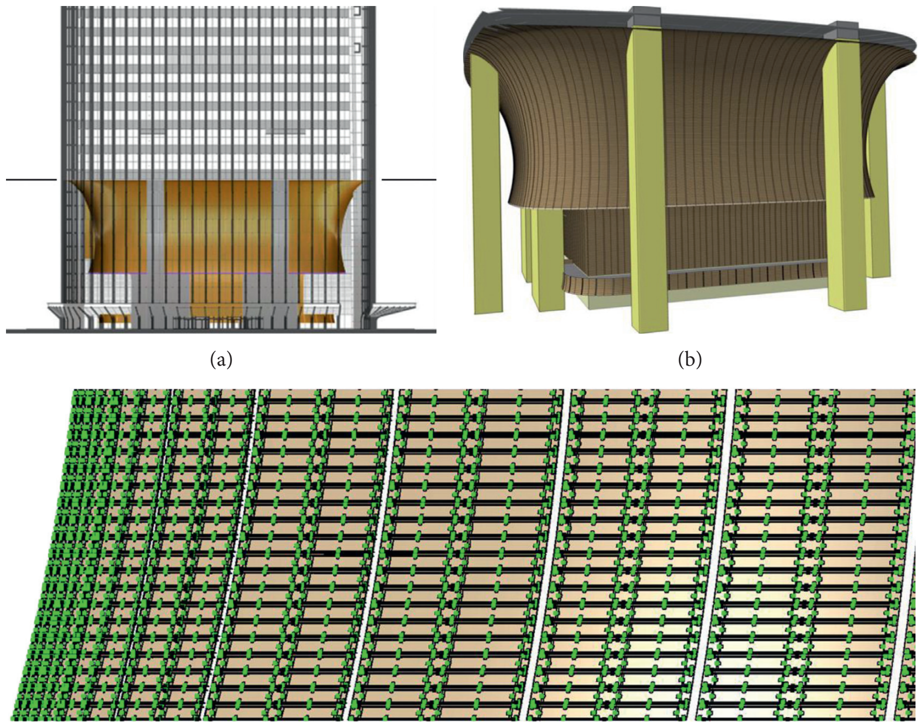
4.2.4. Step 4: Manufacturing Prefabrication Materials Using Digital Information. When the subcontractors responsible for the fabrication of each member received the fabrication drawings, the members were produced through various fabrication methods. In this process, automatic production was performed using a CNC machine, and engineers produced the members in accordance with the fabrication drawings and quality criteria. For example, for the production of the CNC T-BAR, the planar figures of the main members, such as the PLANGE (59A03VW) and WEB (59A03VF), along with the unit member information for connecting these two members (59A03V_U1, 59A03V_U2, and 59A03V_U3) were required, as shown in Figure 11. Moreover, planar figures of the PLANGE (59A03VW2) and WEB (59A03VF2) for the stiffener together with the unit member information for connecting these two members (59A03VS1, 59A03VS2, 59A03VS3, 59A03VS4, and 59A03VS5) were also required. Thus, various data, as shown in Figure 11, are required for fabricating a single unit member, and the information required for quality control must also be calculated from the integrated fabrication model created by professional construction companies. In this process, the professional construction companies provided various types of data required for fabrication drawing production, quality control criteria provisions, and material inspection criteria.

4.2.5. Step 5: Material Warehousing and Inspection. A photograph of each member fabricated in the factories as received is shown in Figure 12, and quality inspection was performed by the product number and the coordinate information extracted from the fabrication model, as listed in Table 3.

4.2.6. Step 6: Material Installation and Quality Control

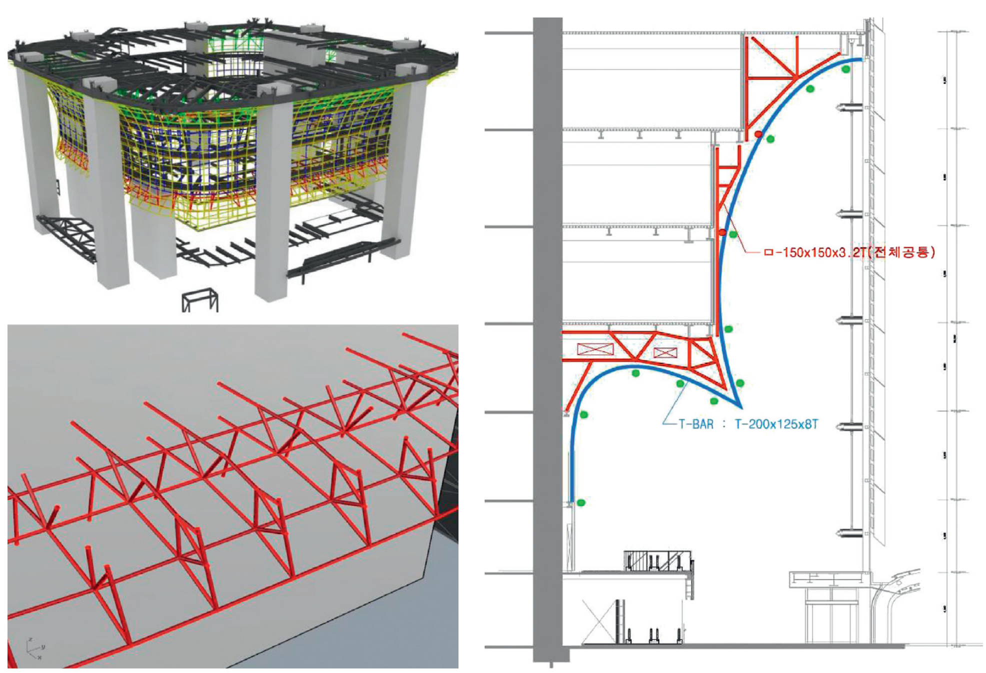
(1) Simulation and 1 : 1 Mock-Up. In the construction phase, a construction simulation was performed to improve the workers' understanding of the entire process before construction, as shown in Figure 13. Issues with quality and constructability were examined in advance by performing a partial 1 : 1 mock-up in the section with the highest construction difficulty, as shown in Figure 14. After these issues were solved, the production of several tens of thousands of fabrication drawings began, and the CNC machine configuration, member fabrication, and construction for member production were performed.

(2) Installation. In the actual construction process, the process in which fabrication drawings are produced from the



(a) (b) (c)

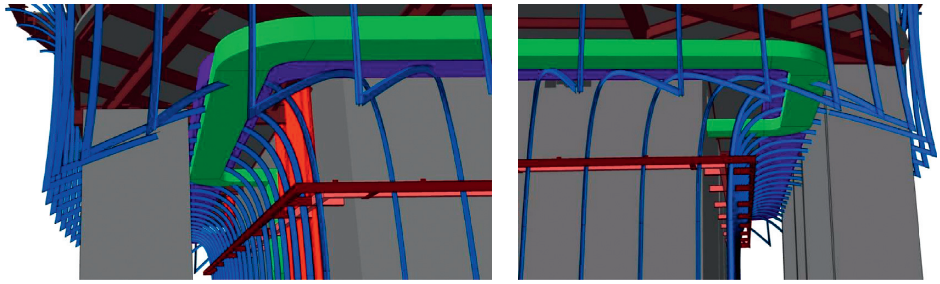
Figure 4: Surface optimization model of the podium.



(a) (b)

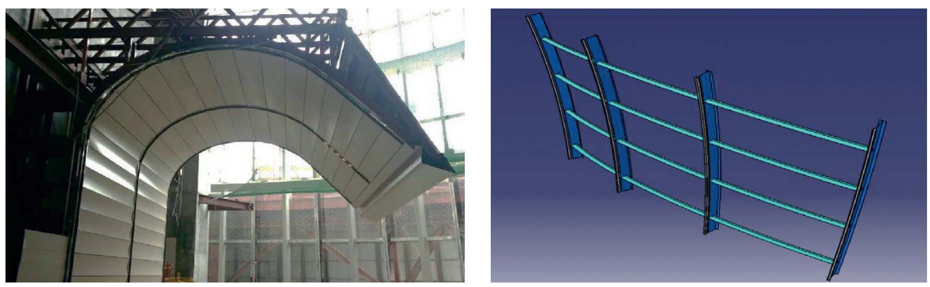
Figure 5: (a) SSS model (green and red). (b) Section view.

integrated fabrication model, members are prefabricated in factories, and construction is performed on the site as shown in Figure 15. If fabrication and construction are performed before the quality examination is completed, serious quality defects may occur. This process is different from those used in existing BIM application projects, in which design errors during construction are examined by converting 2D design drawings into 3D designs. For the precise implementation of



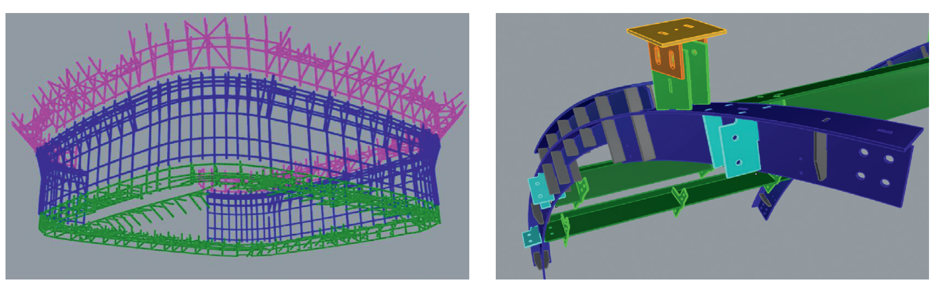
(a) (b)

Figure 6: Clash detection between the secondary steel structure and MEP system.



(a) (b)

Figure 7: Free-form curved surface (a) and CNC T-BAR system (b).



(a) (b)

Figure 8: Fabrication model.

Table 2: List of prefabricated components.

Part	EA	Length/area	Duration (month)	Daily output (EA)
Secondary structure	3,115	8,855.87 m	2	71.20
T-BAR	3,542	9,581.01 m	3	53.67
Form plate	3,435	9,640.41 m	3	52.05
Reveal	1,619	3,339.88 m	3	24.53
NT panel (10T)	17,943	8,181.49 m^2 (curved surface, plane, aperture)	4	203.80
Edge panel (1.6T)	80	250.13 m	0.5	7.27

the digital fabrication, errors must not occur in the production processes, such as manufacturing.

(3) Quality Control of Installed Parts. The quality inspection for the construction results of free-form surfaces was performed using 3D laser scanning. The professional construction companies managed the quality of installation by examining the data extracted from the survey data and integrated fabrication model.

5. Results

By analyzing the case in which the proposed digital fabrication process was applied to a free-form podium

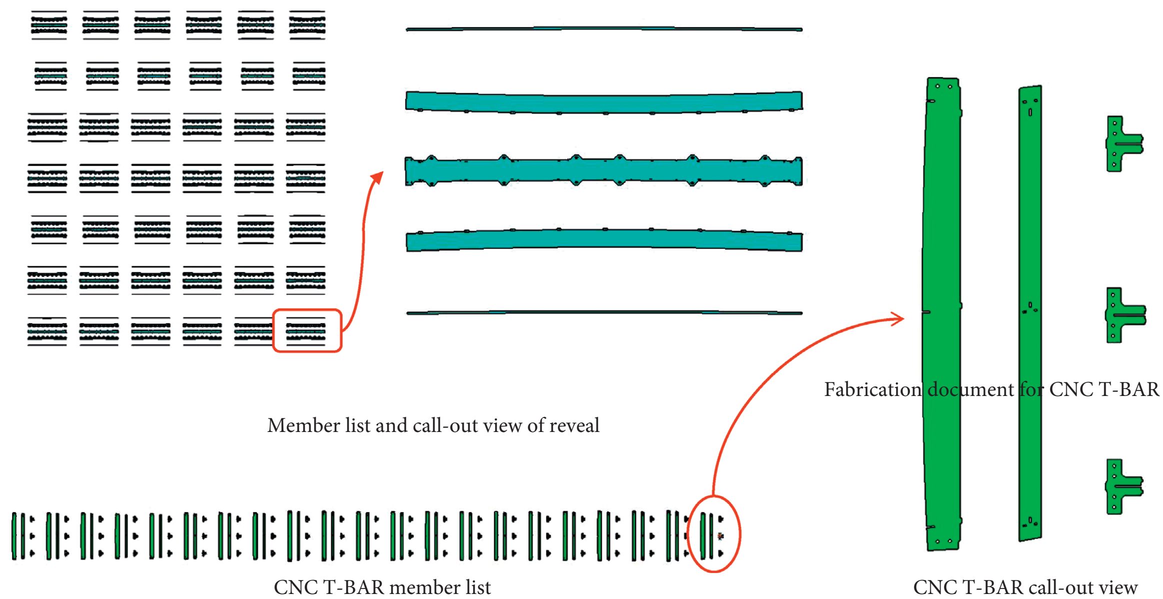


Figure 9: Planar figure example of CNC T-BAR and reveal.

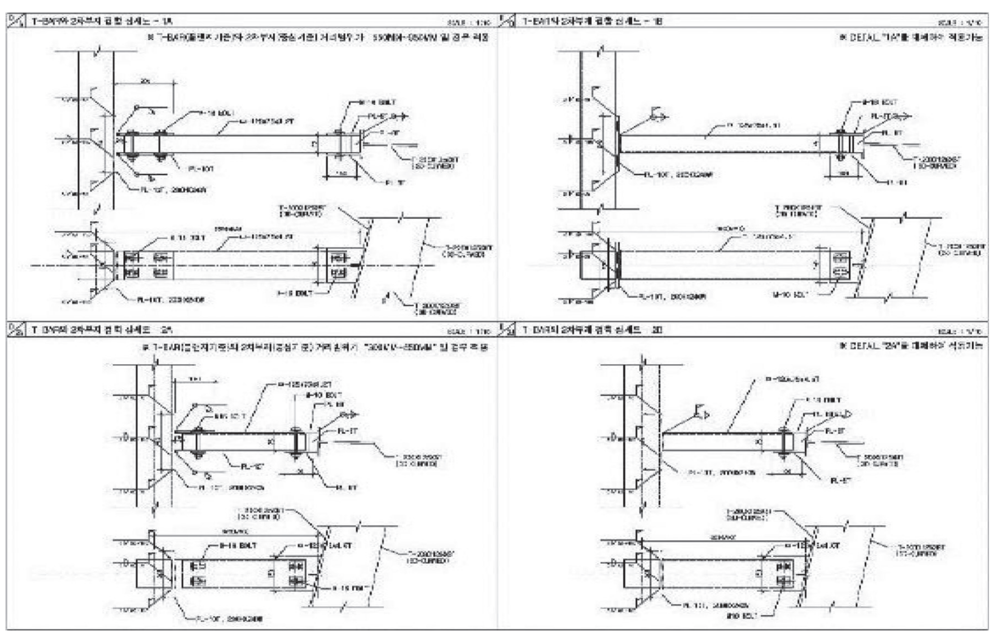


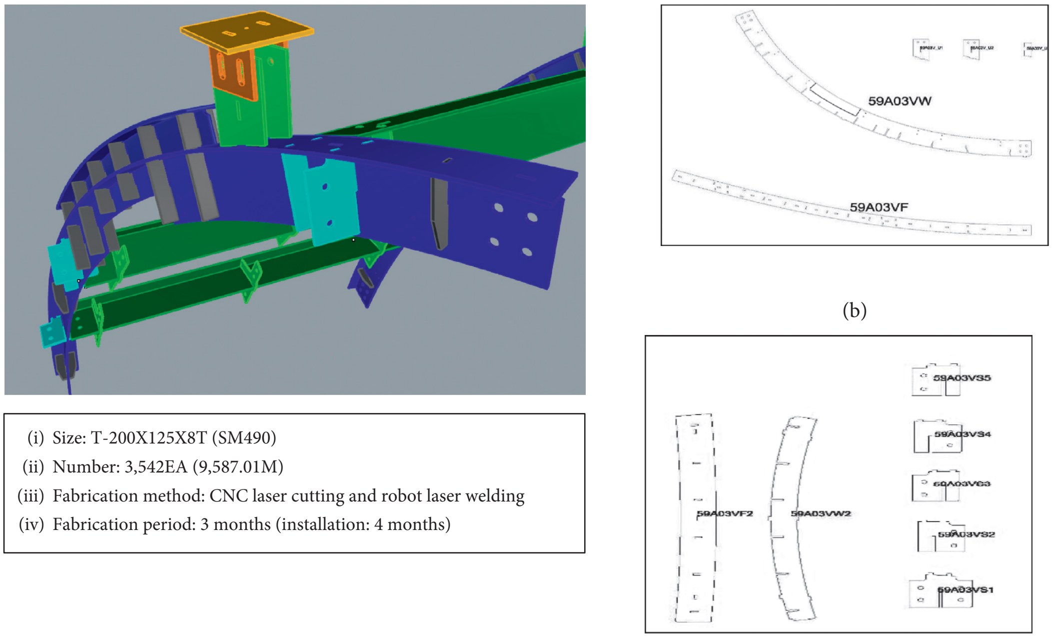
Figure 10: Fabrication shop drawings of CNC T-BAR and secondary steel structure extracted from the fabrication BIM model.

construction project, the unification, simplification, and automation levels of major tasks, such as automation design technology, fabrication drawing production automation technology, and construction quality control technology, were found to be more satisfactory than those of cases which are implemented through traditional BIM implementation methods (establishing the BIM model by using 2D drawings).

5.1. Assessment of the Proposed Process

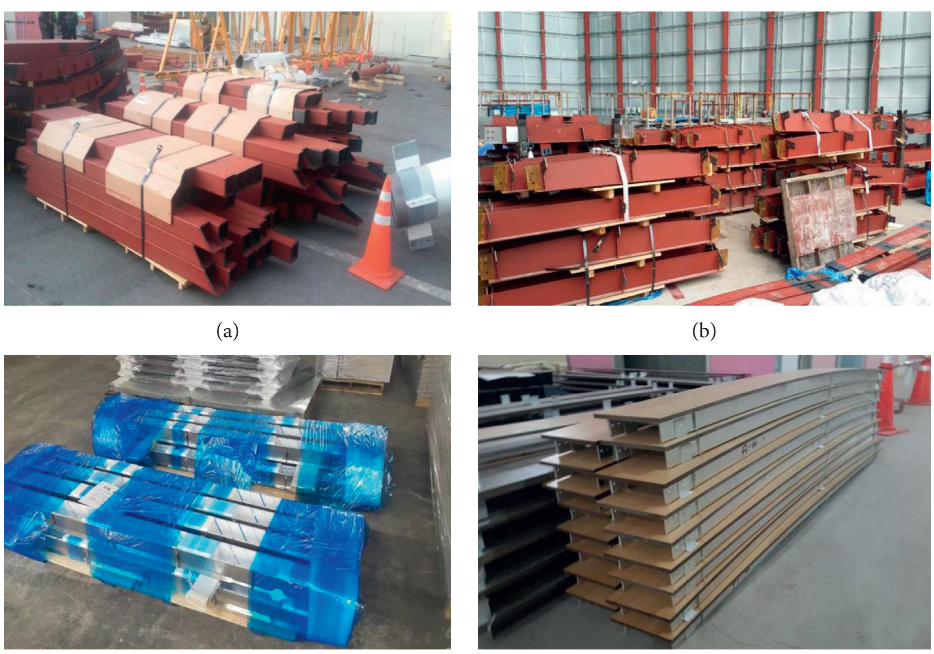
5.1.1. Condition Settings for the Evaluations

(1) Multiserver Queuing Model (M/M/s). A digital fabrication company provides the contractor, subcontractor, and construction project manager participating in the construction with design and engineering models for fabrication and quality inspection. Therefore, in the queuing system, the company that provides the digital fabrication service becomes the server, and the contractor, subcontractor, and construction project manager that receive information from the server and participate in the construction of free-form parts become the customers. There are various queuing models depending on the probabilities of the arrival times of customers and the service time of the server. However, in this study, a multiserver queuing model was utilized, as shown in Figure 16, under the assumption that the digital fabrication company input multiple servers.



(a) (b) (c)

Figure 11: Fabrication information of a CNC T-BAR.



(a) (b) (c) (d)

Figure 12: Warehousing of SSSs, T-BARS, reveals, and NT panels.

In the multiserver queuing model, the frequency with which the server, i.e., the digital fabrication company, receives a request for information on the construction of free-form parts is random. Considering this randomness, the time at which a customer arrives at the queue to receive the service is generally assumed to be an exponential distribution. In addition, the service time during which the information request of the customer is dealt with by the company is random, and the service time of the server is also assumed to be an exponential distribution [37]. Moreover, for most of the general BIM application construction projects, one BIM person stays on the site [40]. However, for the digital fabrication of free-form parts, multiple personnel are generally input because the input company can minimize

Table 3: Member list and information samples for quality inspection of CNC T-BAR.

Product no.	Start (top or left)			End (bottom or right)			Straight line (mm)
	$x1$	$y1$	$z1$	$x1$	$y1$	$z1$	
401IN1	20,917	15,879	17,754	19,537	18,911	17,382	3,352
401IN2	17,598	17,725	15,236	17,598	19,264	17,047	2,377
402HD	20,950	−9,629	17,763	20,950	−12,775	17,763	3,145
402IN1	17,661	19,386	17,179	19,445	18,998	17,367	1,836
410AV	26,382	12,636	19,235	26,382	12,636	16,300	2,935
410BR11	25,542	14,302	17,763	26,043	15,663	17,763	1,450
410BR11	25,542	14,302	17,763	26,043	15,663	17,763	1,450
410BR12	24,982	12,780	17,763	25,483	14,141	17,763	1,450

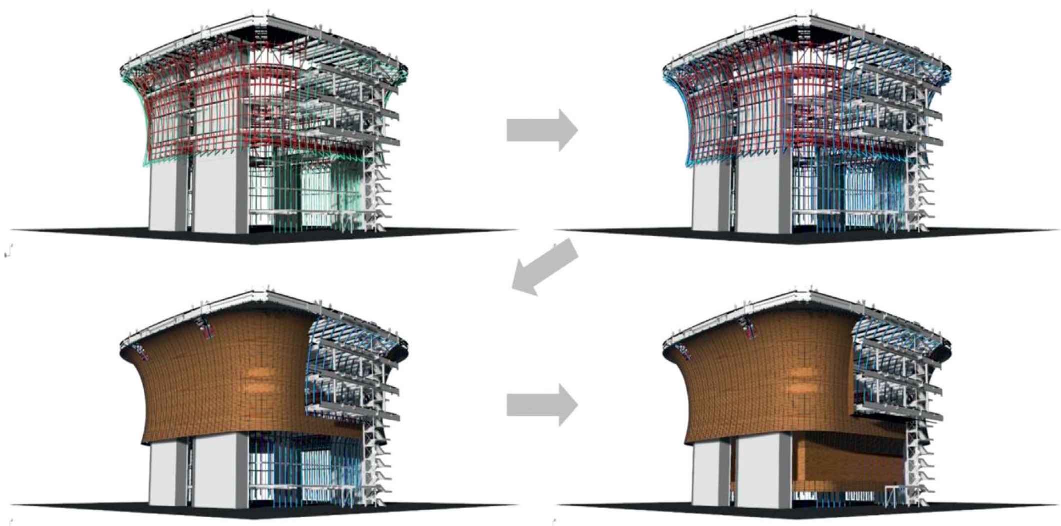
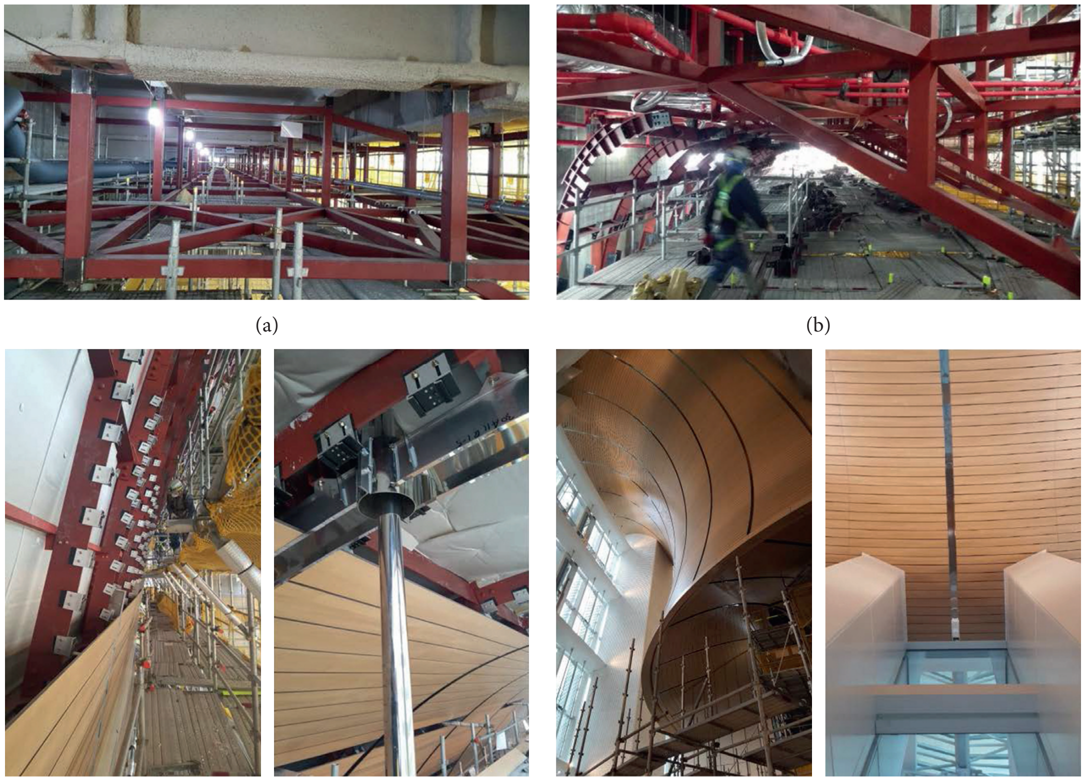


Figure 13: Construction simulation (1st: SSS and CNC T-BAR; 2nd: reveal; 3rd: high-level NT panel; 4th: edge and low-level NT panel).

(a) (b)

Figure 14: 1 : 1 mock-up.



(a) (b)

(c) (d)

Figure 15: Site installation: (a) secondary steel structure; (b) CNC T-BAR; (c) NT panel; (d) finished status.

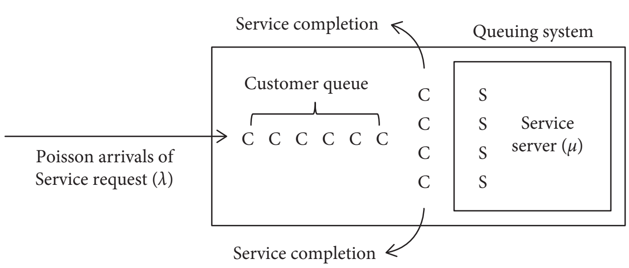


Figure 16: Multiserver queuing system ("C" represents a customer and "S" a server).

effects on subsequent processes when it completes its work within a short period of time. Therefore, the multiserver queuing model includes the following assumptions:

(i) The interarrival times follow an exponential distribution with an average of $1/\lambda$

(ii) The service time follows an exponential distribution with an average of $1/\mu$

(iii) The queuing system has s servers

(iv) The server utilization rate (ρ) is defined as $\lambda/s\mu$

(v) The queuing system is infinite

(vi) The queuing service rule: FCFS (first come, first served)

5.2. Performance Indicators. When the performance of the construction companies that specialize in digital fabrication is analyzed through the multiserver queuing model, it is possible to analyze basic performance measures for the number of customers and waiting time, as shown in Figure 17, and perform probability analysis for the number of customers and waiting time in the queuing system.

5.2.1. Basic Performance Measure Analysis. The performance of the queuing system can be analyzed using the following two measures: (1) How many customers are generally waiting in the queuing system? (2) How long do the customers generally wait? These two measures are generally expressed with mean values (expected values). Four specific performance measures can be defined based on whether only the customers in the queue or all customers in the queuing system will be considered:

(i) L = the average number of customers in the system including those in service

(ii) L_q = the average number of customers in the queue excluding those in service

(iii) W = the average waiting time of each customer in the system (including the service time)

(iv) W_q = the average waiting time of each customer in the queue (excluding the service time)

The basic equations for deriving the performance measures of the multiserver queuing model (L, L_q, W, W_q) are shown below:

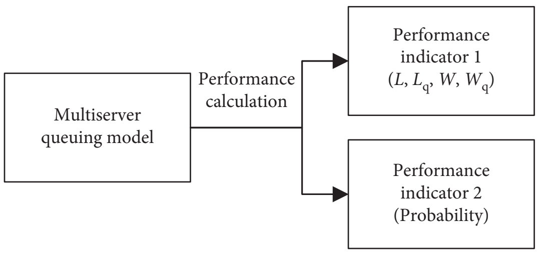


Figure 17: Performance calculation.

$$P_0 = \frac{1}{\sum_{n=0}^{s-1}\left((\lambda/\mu)^n/n!\right) + \left((\lambda/\mu)^s/s!\right)\left(1/(1-\lambda/s\mu)\right)},$$
$$L_q = \frac{P_0(\lambda/\mu)^s\rho}{s!(1-\rho)^2} = \frac{P_0\lambda^{s+1}}{(s-1)!\mu^{s-1}(s\mu-\lambda)^2},$$
$$W_q = \frac{L_q}{\lambda},$$
$$W = W_q + \frac{1}{\mu}. \quad (1)$$

The most important formula for calculating the basic performance measures in the queuing model is Little's formula, which represents the direct relationship between L and W, as shown in (2) [48]. Equation (2) also applies for L_q and W_q. Thus, if either L, L_q or W, W_q is analyzed, the other performance measures can be immediately obtained. This enables a basic status analysis of the service to be performed.

$$L = \lambda W \ (\lambda\text{: mean arrival rate}). \quad (2)$$

5.2.2. Probability Analysis for the Number of Customers and Waiting Time in the System. Through the queuing model, a probability analysis for the status of the queuing system, including the number of customers in the system and waiting time, is possible. If the server utilization rate (ρ) is high, the system condition may deteriorate, and costs may result owing to waiting time increases. If this waiting cost is relatively higher than the server input cost, problems with economic efficiency may occur. In the case of free-form building projects, severe problems with quality may occur in addition to problems with economic efficiency. Therefore, the performance of the company must be evaluated by predicting how many customers are in the queuing system on a probabilistic basis. P_n represents the probability of a stable state when there are n customers in the system:

$$P_n = C_n P_0,$$
$$C_n = \frac{\lambda_{n-1}\lambda_{n-2}\cdots\lambda_0}{\mu_n\mu_{n-1}\cdots\mu_1} = \begin{cases} \dfrac{(\lambda/\mu)^n}{n!}, & n = 1, 2, \ldots, s, \\[2ex] \dfrac{(\lambda/\mu)^n}{s!s^{n-s}}, & n = s+1, S+2, \ldots. \end{cases} \quad (3)$$

The probability of the waiting time of a customer in the system (t) can be expressed as follows. Equation (4) represents the probability that the waiting time of a customer in the system is longer than t, and equation (5) represents the probability that the waiting time in the queue is longer than t:

$$P(W > t) = e^{-\mu t}\left[1 + \frac{P_0(\lambda/\mu)^s}{s!(1-\rho)}\left(\frac{1 - e^{-\mu t(s-1-\lambda/\mu)}}{s-1-\lambda/\mu}\right)\right], \quad (4)$$

$$P\left(W_q > t\right) = \left(1 - \sum_{n=0}^{s-1} P_n\right)e^{-s\mu(1-\rho)t}. \quad (5)$$

5.3. Data Collection for Analyzing Quantitative Project Performance and the Queuing Model. In the case project, the members produced through the fabrication drawings provided by the digital fabrication company are listed in Table 3. In the case of the aperture NT panel, if it is assumed that one fabrication drawing in the form of a planar figure is required for one member, as fabrication drawings for the front and rear processing are required, a total of 36,274 fabrication drawings must be created. During the total service period of seven months, nine engineers from professional construction companies were input (one professional engineer, one special engineer, one advanced engineer, four intermediate engineers, and two beginner engineers). Detailed information is presented in Table 4.

It was found that they participated in the project for a total of 6,574 h during the period of seven months. As the nine workers also participated in projects different from this case project, a total of 52,441 fabrication drawings could have been produced arithmetically had they participated in this case project on a full-time basis (a total of 9,504 h). Based on these data, the daily mean arrival rate (λ) for the fabrication drawing request becomes 274.80 (=36,274 copies of drawings/132 day for six months). If this is converted based on the number of the personnel, the mean arrival rate (λ) is 30.53 (=274.80/9). Using the assumption that the nine engineers work on a full-time basis, the daily mean service rate (μ) becomes 340.53. If this is converted based on the number of workers, the mean service rate (μ) becomes 37.84. Accordingly, the server utilization rate ($\rho = \lambda/s\mu$) is calculated to be 0.81 ($= 274.80/(9 * 37.84)$). In addition, the server idle rate, $(1-\rho)$, is calculated to be 0.19.

This means that the digital fabrication process is active only 81% of the time. The remainder of the time is utilized for performing other tasks explained above. This includes a month of preparation period, work plan, and environment establishment for the professional construction company responsible for the digital application work before the contract. In detail, the establishment work of the fabrication BIM model is included in the fabrication documentation work (6 months). Furthermore, initial preparation and quality control for drawing extraction are included in the drawing extraction work (6 months), and thus, the 19% server idle rate is by no means too high and is one of the works that must be performed.

Table 4: Input manpower for digital fabrication works.

Month	Worker level					
	Professional	Special	Advanced	Intermediate (total hours for 4 workers)	Beginner (total hours for 2 workers)	Total hours
1st month	92	120	256	446	86	1,020
2nd month	145	194	249	554	226	1,368
3rd month	28	120	229	173	212	762
4th month	25	214	262	594	296	1,391
5th month	20	228	192	600	390	1,430
6th month	22	104	222	88	167	603
Total (h)	332	980	1,410	2,475	1,281	6,574

5.4. Performance Measurement Model Analysis Results

5.4.1. Basic Performance Measure Analysis. As a result of analyzing the average performance of nine personnel input for digital fabrication, the server utilization rate ($\rho = \lambda/s\mu$) was 0.81, a value less than 1, which is the requirement for the queue to reach the stable state. This indicates that the professional construction companies can provide normal services to customers in need of fabrication drawings in the queuing system. As for the basic performance measures, L was 9.13 cases, L_q was 1.87 cases, W was 0.03 d, and W_q was 0.01 d. Thus, the average waiting time of a customer is approximately 0.24 h (14.4 min), which is 0.03 of a day (based on 8 h).

5.4.2. Probability Analysis for the Number of Customers and Waiting Time. In the queuing system, P_n represents the probability that during the stable state, there are $n (n = 1, 2, 3, \ldots)$ customers in the system. Figure 18 shows the probability according to the number of fabrication drawings in the queuing system of the case project.

If the goal is to maintain the requests for fabrication drawings to less than 15 cases in the queuing system over 90% of the time, the equation $P_0 + P_1 + \cdots + P_{15} = 0.9003 \geq 0.90$ is valid. The value of P_0 was 0.0005, indicating that this queuing system is always waiting for fabrication drawing production. As shown in Figure 18, the value of P_7 is the highest at 0.1180, followed by P_6 (0.1137), P_8 (0.1071), P_5 (0.0940), and P_9 (0.0864). However, a customer did not wait long in most cases because nine servers were input. This means that the professional construction companies can provide information in time without customers having to wait. There was almost no waiting time for the service to request and receive fabrication drawings because the fabrication drawing production method was automated through the integrated fabrication model described above.

The probability that the waiting time of a customer has a certain value was analyzed to more accurately judge the productivity of the project. The probability of waiting 10 min or longer was analyzed. As a result, $P(W > t)$ was 0.5762, indicating that the probability of waiting 10 min or longer in the queuing system to receive fabrication drawings was 57.6%. Moreover, $P(W_q > t)$ was 0.1137, indicating that the probability of waiting 10 min or longer in the queue to receive fabrication drawings was 11.37%. This means that a customer does not wait for long to receive fabrication drawings and that the service status for providing fabrication drawings is excellent.

5.5. Comparative Analysis of the Work Productivities of the Proposed and Conventional Methods. Existing case analysis studies were utilized to compare the productivity of the proposed digital fabrication process with that of the conventional method [40, 49]. Table 5 presents the BIM conversion design personnel input in various studies. While BIM personnel were inputted in the construction phase and performed BIM-related requests for information (RFIs), the digital fabrication company was input during a short period of time for the construction of the free-form podium region. Owing to the nature of the construction, high-level engineering and project management capabilities, such as structural system selection, discussion of other processes, and detail determination, are required despite completion of the free-form construction. Moreover, the determined work period must be followed because subsequent processes can be significantly affected. Although the man/month inputs of the conventional and proposed methods are similar, there are considerable differences in work performance. The BIM personnel supporting the design conversion respond to the RFIs of the project participants, and they are focused on improving the consistency of the BIM model during the remaining time. However, for cases where free-form projects require tens of thousands of fabrication drawings, improving the consistency of the BIM model is not the goal. The focus is on achieving zero errors in the final implementation through the information extracted from the BIM model to ensure construction quality. Therefore, digital technology must be aggressively utilized to implement precise construction quality and produce the tens of thousands of fabrication drawings required for short-term construction. In other words, the automation design technology was aggressively introduced to construct an integrated BIM model capable of providing information on the design, fabrication, and construction within a very short period of time. Furthermore, the application of the BIM model was done at a very high level by performing factory fabrication through the technology to automatically produce tens of thousands of fabrication drawings from the BIM model and manage the construction quality.

When the performance of the BIM personnel utilizing the multiserver queuing model is compared with the existing

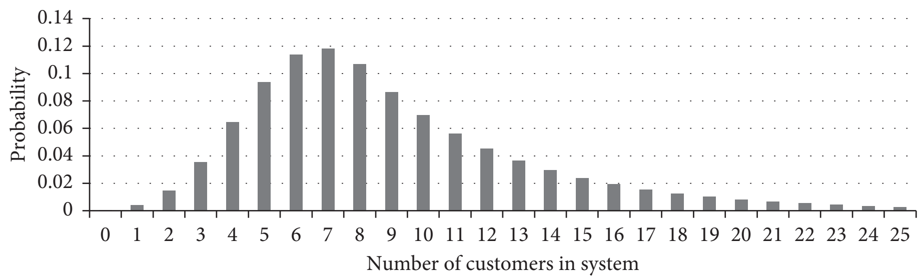


Figure 18: Probability of the number of BIM RFIs in the queuing system.

Table 5: Comparison of labor input and findings.

Category	BIM labor [49]	BIM labor [40]	Specialty contractor (6,574 h)	Specialty contractor (9,504 h)
Period (M)	20	13–17	7	7
No. of workers	1	1–3	9	9
Finding	BIM RFI		Fabrication documentation	
No. of findings	244	214–381	36,274	52,441

study cases, the high performance of the professional construction companies of this study can be observed objectively (Table 6). Kim et al. [40] analyzed performance of BIM-based digital fabrication using the RFIs supported while the BIM personnel remained at the site for the construction phase of the BIM application project (case projects 1–4 in Table 6). The mean arrival rate (λ: 0.748–1.094) and mean service rate (μ: 1–3) were extremely low compared to the mean arrival rate (λ: 26.17) and mean service rate (μ: 37.84) of the professional construction companies. This is because the number of the fabrication members required in the course of implementing the shapes of free-form curved surfaces (36,274) was higher than the BIM RFIs. Such results were obtained even though the company did not work on a full-time basis. If the company had worked on a full-time basis and if BIM technology was utilized at a very high level, such as for automation design, automatic fabrication drawing production, and factory fabrication based on 3D model information, 52,441 fabrication drawings could have been produced.

6. Discussion

In general, conventional fabrication methodologies have relied on 2D CAD and numerous paper documents, which have caused various problems, such as difficulties and errors in design, poor fabrication quality, and increased construction difficulty. BIM, which is a simple support technology, has been applied to supplement these processes. However, the BIM data cannot be used to manage the entire life cycle of the project, including the design, fabrication, and installation phases. In particular, it is difficult to obtain effects such as cost reduction, schedule reduction, and information provision to improve work productivity throughout the production life cycle.

The BIM-based digital fabrication proposed in this study is a methodology for steadily managing and utilizing a single set of BIM data throughout the entire life cycle of the project, from the initial stage to the construction and quality control stages. To determine the quantitative effect of the proposed digital fabrication process, the amount of work performed in relation to the personnel and time input, i.e., the performance, was analyzed. The resulting values of mean independent rate (μ), mean service rate (μ), server efficiency ($\rho/s\mu$), and server efficiency ($1-\rho$) proved that the proposed process exhibits satisfactory performance.

This means that the proposed BIM-based digital fabrication service is very efficient in providing the right information to the right participants in the design, fabrication, and construction work. To optimize the process through digital communication, it is necessary to produce and provide high-level and effective information. These tasks can be produced through BIM and automation technologies, and the man/months carrying them out are not significantly different from the existing personnel. In other words, this study reveals that by improving the process, considerable improvements can be achieved without increasing manpower or time.

7. Conclusions

7.1. Study Summary. In this study, a digital fabrication process during the life cycle of a building project was proposed based on the free-form podium construction case. The main steps are as follows:

(1) Free-form part shape optimization

(2) Structure system selection for NT panel shape control

(3) Fabrication drawing production

(4) Digital manufacturing

(5) Material receipt and inspection

(6) Construction and measurement

The proposed process is a generalized model that can be universally applied even though the characteristics of digital

Table 6: Comparison of performance indicators in the queuing model.

Performance indicators	Case projects [40]				Specialty contractor (9,504 h)
	Project 1	Project 2	Project 3	Project 4	
Period (day)	352	286	308	374	154
No. of workers (s)	2	1	1	3	9
Mean arrival rate (λ)	1.082	0.748	1.094	0.826	26.17
Mean service rate (μ)	2	3	1	1.67	37.84
Server utilization ($\rho = \lambda/s\mu$)	0.271	0.249	1.094	0.165	0.81
Server efficiency ($1 - \rho$)	0.729	0.751	N/A	0.835	0.19

fabrication might change owing to numerous variables, such as the target project, part, type, form, scale, and material. Moreover, a productivity evaluation model was proposed using the queuing model to verify the productivity of the case project implemented through the proposed process. Basic performance measures were verified, and the number of customers and waiting time probabilities were calculated using the multiserver queuing model as the basic framework. Through a comparison with the conventional 2D-based fabrication and installation method, an improvement in productivity was demonstrated.

8. Contributions

The BIM-based digital fabrication methodology provides error minimization, time reduction, and collaboration efficiency reinforcement in performing tasks such as 3D fabrication, model construction, panel design automation, fabrication-drawing production automation, and 3D status measurement data examination for quality control. Moreover, it enables communication, collaboration, and coordination with construction companies, construction project managers, and professional construction companies hired for the construction of free-form exterior panels and low structural members using BIM data.

The performance analysis, based on a multiserver queuing model, provides a quantitative analysis methodology and uses data obtained throughout the project, such as the number of fabrication drawings, input personnel, input period, and input time. The results revealed that the professional construction companies performing digital fabrication could automatically produce the tens of thousands of fabrication drawings required for free-form shape implementation by applying various digital technologies that utilize 3D models and making these drawings available to the project participants. This proposed digital technology is different from design conversion, which converts the existing 2D design drawings into 3D models.

8.1. Limitations and Future Work. While this study focused on the performance of the personnel of professional construction companies, the productivity of the computers and robots utilized in the digital fabrication process were not considered. Had they been considered, the performance of digital fabrication would have been verified more specifically. Moreover, the cost of digital fabrication was not directly input into the analysis target, and it was indirectly reflected through the comparison of the service rate and waiting time. The limitations of these two factors will be analyzed in connection with the evaluation methodology based on the queuing model in a future study.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (no. 20161510300420).

References

[1] O. Zwikael, Y. Cohen, and A. Sadeh, "Non-delay scheduling as a managerial approach for managing projects," *International Journal of Project Management*, vol. 24, no. 4, pp. 330–336, 2006.

[2] J. L. Celine, *The evolution of the use of prefabrication techniques in Hong Kong construction industry*, Ph.D. thesis, Hong Kong Polytechnic University, Hong Kong, China, 2009.

[3] V. R. Kamat, J. C. Martinez, M. Fischer, M. Golparvar-Fard, F. Peña-Mora, and S. Savarese, "Research in visualization techniques for field construction," *Journal of Construction Engineering and Management*, vol. 137, pp. 853–862, 2010.

[4] J. Lee and J. Kim, "BIM-based 4D simulation to improve module manufacturing productivity for sustainable building projects," *Sustainability*, vol. 9, no. 3, p. 426, 2017.

[5] McGraw Hill Construction, *The Business Value of BIM for Construction in Major Global Markets: How Contractors around the World Are Driving Innovation with Building Information Modeling*, H. M. Bernstein, Ed., SmartMarket Report, Bedford, MA, USA, 2014.

[6] R. S. Weygant, *BIM Content Development: Standards, Strategies, and Best Practices*, Wiley, Hoboken, NJ, USA, 2011, ISBN: 978-0-470-58357-9.

[7] N. Č. Babič, P. Podbreznik, and D. Rebolj, "Integrating resource production and construction using BIM," *Automation in Construction*, vol. 19, no. 5, pp. 539–543, 2010.

[8] M. Hamid, O. Tolba, and A. El Antably, "BIM semantics for digital fabrication: a knowledge-based approach," *Automation in Construction*, vol. 91, pp. 62–82, 2018.

[9] C. B. Tatum, J. A. Vanegas, and J. M. Williams, *Constructability Improvement Using Prefabrication, Preassembly, and Modularization*, Bureau of Engineering Research, University of Texas at Austin, Austin, TX, USA, 1987.

[10] P. Paevere and C. MacKenzie, *Emerging Technologies and Timber Products in Construction*, Australian Forest and Wood Products Research and Development Corporation, Melbourne, Australia, 2006.

[11] S. McGuinness and J. Bennett, "Examining the link between skill shortages, training composition and productivity levels in the construction industry: evidence from Northern Ireland," *International Journal of Human Resource Management*, vol. 17, no. 2, pp. 265–279, 2006.

[12] G. Seaden and A. Manseau, "Public policy and construction innovation," *Building Research & Information*, vol. 29, no. 3, pp. 182–196, 2001.

[13] A. Crowley, "Construction as a manufacturing process: lessons from the automotive industry," *Computers & Structures*, vol. 67, no. 5, pp. 389–400, 1998.

[14] D. Veeramani, H. P. Tserng, and J. S. Russell, "Computer-integrated collaborative design and operation in the construction industry," *Automation in Construction*, vol. 7, no. 6, pp. 485–492, 1998.

[15] D. Gann, "Putting academic ideas into practice: technological progress and the absorptive capacity of construction organizations," *Construction Management and Economics*, vol. 19, no. 3, pp. 321–330, 2001.

[16] A. Agkathidis, J. Bettum, M. Hudert, and H. Kloft, *Digital Manufacturing in Design and Architecture*, BIS, Amsterdam, Netherlands, 2010.

[17] N. Dunn, *Digital Fabrication in Architecture*, Laurence King Publishing Ltd., London, UK, 2012.

[18] I. Agustí-Juan, F. Müller, N. Hack, T. Wangler, and G. Habert, "Potential benefits of digital fabrication for complex structures: environmental assessment of a robotically fabricated concrete wall," *Journal of Cleaner Production*, vol. 154, pp. 330–340, 2017.

[19] F. Gramazio and M. Kohler, *Digital Materiality in Architecture*, Lars Müller Publishers, Baden, Switzerland, 2008.

[20] F. Gramazio, M. Kohler, and S. Langenberg, *FABRICATE: Negotiating Design & Making*, GTA Verlag, Zurich, Switzerland, 2014.

[21] S. H. Koh, N. H. Ham, J. S. Lee, S. W. Yoon, and J. J. Kim, "Comparison analysis of BIM level in the domestic and overseas BIM projects—focused on BIM journals and award winning projects," *Journal of KIBIM*, vol. 7, no. 2, pp. 25–35, 2017.

[22] J. S. Won, J. J. Lee, and G. Lee, "A case study on BIM collaboration and information management methods," *Journal of the Architectural Institute of Korea Planning & Design*, vol. 24, no. 8, pp. 25–32, 2017.

[23] S. J. Jang and G. Lee, "Analysis of technical requirement for implementation of multi-trade prefabrication," *Conference of the Korean Institute of Building Construction, the Korean Institute of Building Construction*, vol. 16, no. 1, pp. 113-114, 2016.

[24] Skanska, *Prefabrication Case Study, Miami Valley Hospital*, NYC Healthcare Symposium, Philadelphia, PA, USA, 2011.

[25] Mortenson, "Prefabrication: benefits & drivers for successful implementation," in *Prefabrication Research Study Results*, M. Rosenquist and B. Gregor, Eds., SMACNA, Chantilly, VA, USA, 2014.

[26] W. C. Lim and J. K. Lee, "A study on expressive characteristics of pavilion applying digital fabrication," *Journal of KISD*, vol. 10, no. 6, 2015.

[27] L. Sass and M. Botha, "The instant house: a model of design production with digital fabrication," *International Journal of Architectural Computing*, vol. 4, no. 4, pp. 109–123, 2006.

[28] R. A. Buswell, R. C. Soar, A. G. F. Gibb, and A. Thorpe, "Freeform construction: mega-scale rapid manufacturing for construction," *Automation in Construction*, vol. 16, no. 2, pp. 224–231, 2007.

[29] S. Jang and G. Lee, "Process, productivity, and economic analyses of BIM–based multi-trade prefabrication—a case study," *Automation in Construction*, vol. 89, pp. 86–98, 2018.

[30] B. G. de Soto, I. Agustí-Juan, J. Hunhevicz et al., "Productivity of digital fabrication in construction: cost and time analysis of a robotically built wall," *Automation in Construction*, vol. 92, pp. 297–311, 2018.

[31] A. Fazel and A. Izadi, "An interactive augmented reality tool for constructing free-form modular surfaces," *Automation in Construction*, vol. 85, pp. 135–145, 2018.

[32] J. Knippers, "Integriertes Entwerfen im digitalen Prozess," *Bautechnik*, vol. 91, no. 4, pp. 257–261, 2014.

[33] X. Li, G. Q. Shen, P. Wu, H. Fan, H. Wu, and Y. Teng, "RBL-PHP: simulation of lean construction and information technologies for prefabrication housing production," *Journal of Management in Engineering*, vol. 34, no. 2, article 04017053, 2018.

[34] M. Nahangi and C. T. Haas, "Automated 3D compliance checking in pipe spool fabrication," *Advanced Engineering Informatics*, vol. 28, no. 4, pp. 360–369, 2014.

[35] J. Wang, X. Wang, W. Shou, H.-Y. Chong, and J. Guo, "Building information modeling-based integration of MEP layout designs and constructability," *Automation in Construction*, vol. 61, pp. 134–146, 2016.

[36] H. Said, "Modeling and likelihood prediction of prefabrication feasibility for electrical construction firms," *Journal of Construction Engineering and Management*, vol. 142, no. 2, article 04015071, 2016.

[37] S. Frederick and S. Mark, "Introduction to management science," in *A Modeling and Case Studies Approach with Spreadsheets*, Chapter 11, McGrawHill, New York, NY, USA, 4th edition, 2010.

[38] N. K. V. Truong, Y. Choi, I. Kim, S. Shin, and W. J. Hwang, "A probabilistic approach to workflow time analysis for business process management," *International Journal of Social Science Studies*, vol. 5, no. 12, pp. 811–815, 2010.

[39] N.-H. Ham and J.-J. Kim, "A case study on BIM operating and performance measurement in construction phase," *Journal of KIBIM*, vol. 5, no. 2, pp. 1–11, 2015.

[40] H. J. Kim, M. Y. Yoo, J. J. Kim, and C. S. Choi, "Performance analysis of BIM labor using case analysis," *Journal of KIBIM*, vol. 7, no. 3, pp. 31–39, 2017.

[41] N. Sadeghi, A. Robinson Fayek, and N. Gerami Seresht, "Queue performance measures in construction simulation models containing subjective uncertainty," *Automation in Construction*, vol. 60, pp. 1–11, 2015.

[42] D. W. Halpin and S. L. Riggs, *Planning and Analysis of Construction Operations*, John Wiley and Sons, Hoboken, NJ, USA, 1992.

[43] J. Gerring, "What is a case study and what is it good for?," *American Political Science Review*, vol. 98, no. 2, pp. 341–354, 2004.

[44] R. K. Yin, *Case Study Research: Design and Methods*, SAGE Publications, Newbury Park, CA, USA, 2nd edition, 1994.

[45] K. M. Eisenhardt, "Building theories from case study research," *Academy of Management Review*, vol. 14, no. 4, pp. 532–550, 1989.

[46] D. Holzer, *The BIM Manager's Handbook: Guidance for Professionals in Architecture, Engineering, and Construction. Best Practice BIM ePart 1*, Wiley, Hoboken, NJ, USA, 2015.

[47] S. J. Kim, *Construction Method of 3D Interior and Exterior Panel Using CNC T-BAR*, Korea Intellectual Property Rights Information Service, Daejeon, South Korea, 2017.

[48] J. D. C. Little, "A proof of the queuing formula: $L = \lambda W$," *Operations Research*, vol. 9, no. 3, pp. 383–387, 1961.

[49] E.-J. Kim, J.-H. Kim, and Y.-K. Huh, "A case study on practical uses of BIM in building construction," *Journal of the Architectural Institute of Korea Structure & Construction*, vol. 32, no. 12, pp. 69–75, 2016.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 5161579, 12 pages
https://doi.org/10.1155/2019/5161579

Review Article

Mapping Knowledge Domains of Integration in BIM-Based Construction Networks: A Systematic Mixed-Method Review

Bin Guo[1] **and Tao Feng**[2]

[1]*Professor, Faculty of Engineering Economics and Management, School of Public Administration, Institute of Management, Xi'an University of Architecture and Technology, Xi'an, Shaanxi 710000, China*
[2]*Institute of Management, Xi'an University of Architecture and Technology, Xi'an, Shaanxi 710000, China*

Correspondence should be addressed to Tao Feng; 756783706@qq.com

Received 28 November 2018; Revised 6 March 2019; Accepted 28 April 2019; Published 15 May 2019

Academic Editor: Mohammad R. Hosseini

Building information modeling-based construction networks (BbCNs) are teams from several professional organizations working together to assume building information modeling- (BIM-) related assignments on BIM-enabled projects. With a view to achieving a better understanding of the knowledge domains on integration in BbCNs, a systematic mixed-method review of the relevant studies published from 2008 to 2018 is conducted in this study. An "integration pentagon" made up of context, process, organization, task, and actor is used as a theoretical lens to identify and construct knowledge maps describing the integration in BbCNs. The study conducts a comprehensive review upon a bibliometric analysis based on 1019 researches into BIM and a qualitative analysis of 42 carefully selected researches into integration in BbCNs. The findings confirm that the solutions provided by these researches to support integration in BbCNs are altogether technology oriented. The sociotechnical dimensions including context, organization, task, and actor show limitations. More importantly, the major academic contributions of the study lie in offering an objective and systematic analysis of previous researches, revealing the gaps on integration in BbCNs, and advising researchers in future studies regarding the integration pentagon as an all-inclusive analysis tool. These results highlight the status quo of BbCNs knowledge and serve as a dynamic platform to allow other scholars to perform further developments of integration in BbCNs.

1. Introduction

Applying building information modeling (BIM) in delivering construction projects has been on the rise [1, 2]. BIM-enabled projects are delivered through using building information modeling-based construction networks (BbCNs), defined as teams comprising specialist organizations that are contracted to execute BIM-related works on these projects [3]. The capability to increase integration in these BbCNs has been essential BIM [4]. Nevertheless, sustaining integration among members with geographic dispersion from various organizations and disciplines within BbCNs has been regarded to be problematic [5, 6] and thus consequently deserving further exploration.

Although the existing research underlines the importance of integration and explores the factors impacting integration in BbCNs [7], the insufficiency application status of integration in practice still makes reference to the gaps in the body of knowledge (BOK) on integration within BbCNs [5, 8, 9]. At the stage, there is an absence of BOK on integration to guide its development in BbCNs, although Oraee et al. [10] have researched the collaboration in BbCNs. However, it should be emphasized that from the point of view of project management research, the meaning of "collaboration" and "integration" is not consistent, and the "integration" means the synergy of internal systems in a separate unit (that is, the project), which is more responsive to the characteristics of the project [11, 12]. BbCN is a construction network built from a project-based unit, and it is more necessary to study its integration characteristics. This discovery induces a great obstacle in determining the direction for research on integration in BbCNs, which make it difficult to capture frontier highlight or repetitive efforts.

Accordingly, it is urgent to integrate the existing literature, which might fill the gap and indicate future research highlights [13]. To this end, we draw on the research method of the article of Oraee et al. [10] which was published in the International Journal of Project Management (IJPM) in 2017 and analyze the scholarship on integration in BbCNs. In addition, unlike the study of Oraee et al. [10], this research provides an extended version of an extended Leavitt sociotechnical model as the theoretical point to map and analyze the status of existing literatures on the integration in BbCNs. The results are likely to grasp the connotation and characteristic of integration research in BbCNs and reveal the concepts and patterns which have been maintained hidden on this topic. Moreover, the findings will play a positive role in guiding and promoting theoretical research and practical application in this field.

The paper starts with a brief explanation of integration within BbCNs, which is followed by the research method. Research findings are then outlined. In the subsequent section, a discussion of those findings is introduced. The paper folds with a summary of the major points and conclusions.

2. Background

2.1. Integration on Construction Projects. Integration refers to the process of integrating isolated elements or things into an organic whole. The concept of integrated management was first proposed and applied from the information technology (IT) industry and later developed into a field of expertise in project management. In this new management concept and method, integrated concepts are leveraged to guide and manage practical activities [14]. A traditional management mode derives from the theory of division of labor, while this new approach highlights integration thought, and it also fuses and amplifies individual advantages so that improved comprehensive efficiency, along with management activities, is ensured.

An integrated implementation relies on close communications between project participants [15–18]. With the occurrence of CIM (computer integrated manufacturing) propagation and applications of IT into construction activities [19], the essence of integration has experienced a thorough variation over the past few years [20, 21]. In nature, BIM has evolved into the core of cross-organization integration technology to support integration of participants [22]. As BIM is developed into a state-of-the-art technology to facilitate integration in the construction industry, BbCNs appear as a major carrier to foster integration [2, 5, 9] as described below.

2.2. BIM-Based Construction Networks (BbCNs). BIM is a solution to multiparty coordination of innovative technology, and its value depends on a rational organization pattern. Solihin et al. [23] even believe that the traditional project organization model fails to make BIM meet project requirements. Under such circumstances, scholars recognize the necessity of studying the cross-organization application of BIM and putting forward the BbCNs [2]. As BbCN is proposed, construction projects have essentially transitioned to "temporary social networking organizations," [24] indicating that project participants are exposed to a new integration environment. The attainment of the goal and success in BbCNs depends on a closely integrated working and seamlessly information sharing of participants [19, 25–27]. Therefore, many scholars emphasize that we should cultivate the integration environment to transform our traditional ideas so as to better foster integration among BbCN participants [8, 28, 29]. Integration of construction and BbCNs, however, is a complicated system manipulated by many elements [8, 28]. It underlines the necessity of an in-depth analysis by combining the characteristics of integration and the BbCNs [30].

2.3. Theoretical Lens. As recommended by Merschbrock et al. [15], a theoretical lens was applied to translate the findings into understandable messages. This theoretical lens assists researchers in developing explanations so that audiences are allowed to relate the findings to broader aspects and findings are made comparable to other cases. Selecting a theoretical lens enhances the internal validity of findings in the cases of studies through a pattern matching in which researchers compare patterns in established theories with empirically observed patterns [31].

Such systems, including BbCNs, are defined by sociotechnical system (STS) theories as organizational work systems consisting of two subsystems, both socially and technically, that interact with and influence each other [32]. These subsystems integrate effectively with each other provided that the interdependency of the subsystems is clearly recognized [32, 33]. This premise is deemed valid for investigation integration in BbCNs [34] and has provided a theoretical basis for this study.

Sackey et al. [35] reviewed the existing theoretical models to select the most workable for analyzing BbCNs. They concluded that the Leavitt sociotechnical model [36], stereotype though, has evolved adequately and embodies key principles that vividly reflect the working nature in BbCNs. The model has been referred to for a long time in studying technology applications and shows validity in explaining the challenges modern STSs meet [37]. The Leavitt sociotechnical model is associated with technology, task, actor, and organization dimensions. The predictive power of the model, however, grows with the inclusion of new dimensions for specific BbCNs [35, 37]. In the context of innovation, Poirier et al. [38] added several dimensions as *process, context,* and *team* to increase the explanatory power of the model in dealing with modern teams. Sackey et al. [35] extended the model in construction by introducing several analytical concepts to produce a modified model that effectively reflects BIM-related systems.

2.4. Integration Pentagon of BbCNs. In this study, according to the Leavitt sociotechnical model by Leavitt [36] and the extended framework proposed by Poirier et al. [38], an extended Leavitt sociotechnical model has been regarded as a so-called *integration pentagon* of BbCNs as shown in Figure 1.

As defined by prior researches, *context* dimension refers to the specific environment that all these dimensions are set within [38]. *Actor* dimension involves members of an organization who carry out the work. *Process* dimension refers to tools and inventions, and it also possesses a functional dimension [39, 40]. As highlighted in Figure 1, technology and process together compose the technology subset, while other dimensions belong to the social subset in a BbCNs [32]. *Organization* dimension refers to the common relational system of BbCNs, as shown in Figure 1. Structure and term dimensions have been synthesized into the *organization* dimension. *Task* dimension represents the characteristics of BbCNs activities tasks to be completed.

Thus, the system of integration in BbCNs comprises several actors, who use a range of tools and technologist to share their expertise and skills in a context of openness, trust, and mutual respect. They jointly work on the tasks that meet their common goal. The core premise embedded in this system is that all five dimensions are highly interrelated in a nondeterministic manner. These dimensions together lend a transformation of integration process and so on and ultimately catalyze the deeper integration in BbCNs [33]. The precondition has formed the pattern of *integration pentagon* that synthesizes five interrelated dimensions with reciprocal interactions. The *integration pentagon* shown in Figure 1 is adapted as the theoretical lens in this research, which provides a criterion to analyze where the gaps regarding integration in BbCNs are.

2.5. Research Methods. To reach the research objective, a "systematic mixed-methods review" has been used to identify the existing studies, research directions, and gap integrations in BbCNs. Systematic review is a tried and tested method, which is normally counted as superior in the matter of transparency. Compared with systematic ways for flagging up literature reviews, this method can easily be verified through replicating the research setting by other researchers. Aarseth et al. [41], however, pointed out that examining the bibliographic sources only by a review might be of bias, as it leads to subjective judgment and interpretation. Therefore, it is necessary to adopt a systematic mixed-method review in synthesizing literature to ensure breadth and depth in understanding [42]. The systematic mixed-method review synthesizes quantitative and qualitative research to collect and review the available literature on the topic of integration in BbCNs, integrating both the automatic and manual search strategies. To collect as many relevant published research papers, automatic and manual search strategies are turned to.

2.6. Data Collection. By providing a comprehensive and objective summary of the academic research achievements in the field of BIM and BIM-enabled projects over the past decade, we use the authoritative academic database *web of science* (WoS) as the main retrieval platform in this study. The database contains more than 12,000 journals worldwide, which was considered to be sufficient for a broad review on the integration in BbCNs.

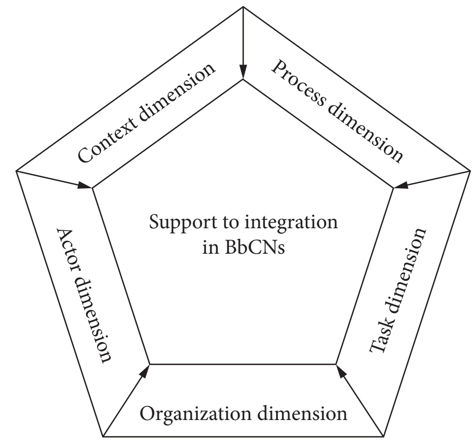


Figure 1: The principal knowledge domains (*integration pentagon*) of BbCNs: a theoretical lens in this study.

2.7. Bibliographic Analysis. In the first stage, a bibliometric analysis method was adapted to review the available studies on BIM-mentioning integration. In this step, common word analysis and common citation analysis were made to explore the distribution and individual signs of literatures in a knowledge domain [43]. This enables researchers to analyze the intellectual landscape of a research area and fulfill their research objectives. There exists a wide range of computer programs for the bibliometric analysis, including VOSviewer, Cite-space, and Gephi. Results from previous researches have offered evidence possible to select computer programs for the bibliometric analysis, and the most important advantage of VOSviewer is that its outputs are closer to the data of WoS [44]. Therefore, VOSviewer has been applied for bibliometric analysis hereafter.

2.8. Qualitative Analysis. In qualitative analysis, what matters is to identify the findings various studies make and any respective gaps by comparing the notions, theories, and themes in a number of retrieved documents. The theoretical lens (*integration pentagon*) facilitates quantitative analysis in this study by serving as a classification code to classify the retrieved documents. The process of qualitative analysis follows the objective proposed by Gough [26] for qualitative phases in mixed.

3. Findings of the Study

3.1. Bibliometric Analysis of the Literature on Integration in BIM. To examine the attention level of integration in the field of BIM-related literature from a more comprehensive perspective, the first step in this study is retrieving the BIM-related studies from WoS. The selected results were all academic papers published during the past decade (2008–2018), with title/abstract/keywords including the terms of "building information modeling," "building information modeling," and "building information modal." The "BIM" was not set as the search keyword because papers of other disciplines that are not within the scope of this study might appear [45]. A total of 1019 BIM-related documents were retrieved as of February 2018. These papers were downloaded and used as core data to support the subsequent analysis in this study.

It has widely been accepted to use citation analysis as an important method to recognize the most influential literature in the field of BIM [46]. Therefore, the data of selected 1019 papers were uploaded to VOSviewer to establish a network of studies based on citations. As suggested by Riaz et al. [46], "fractional counting" served as a counting approach to minimize the influence of sources with plenty of citations on the network [10]. To ensure that the most influential literature can be identified in BIM, the least number of citations in one publication was set as 10. There were 35 papers meeting the threshold and thus were put in the network which is created based on connections and is shown in Figure 2.

Font size distinguishes the degree of citation concentration where larger size represents the higher level of citations concentration. The color of these nodes was set according to the level of the citation concentration, with red being the highest level. The literatures adjacent to the center of the network, as presented in Figure 2, are those with high level of citations, which are information sources and representative view of reference on BIM. An in-depth analysis on these works reveals that these BIM-related influential researches not necessarily focus on integration. Therefore, it can be deduced form Figure 2 that although integration is an important concept in BIM performance, it is not yet the mainstream research direction in BIM-related studies.

The second step in this study is retrieving the relevant studies with regard to integration within the corpus of BIM from the database set in the first step. The target publications were identified through the "searching within results" function of WoS. The function was served through setting integration as a target term in the keyword/abstract/title of the identified list of research papers on BIM (1019 researches). While retrieving, we filtered the results by using the following combinations of terms: "collaboration" OR "interoperability" OR "integrated" OR "coalitions" OR "interaction" OR "coordination" OR "process integration" OR "technology integration" OR "system integration" OR "partner integration" OR "customer integration" OR "supplier integration" OR "manufacturing integration" OR "information integration" OR "interoperability". Accordingly, the number of documents retrieved dropped from 1019 to 90 (ended in February 2018). All of these 90 BIM-related papers regard the integration on their keyword/abstract/title in varying degrees.

A clear display of the main outlets for publishing researches might contribute to offer a more comprehensive perspective to capture the present research state of integration in BbCNs. The VOSviewer was thus utilized to extract and establishes a source network of main outlets from the dataset which was formed by the second step. In the course of operation, the "analysis type," "analysis unit," and "count method" were set to "citations," "sources," and "fractional counting," respectively. In the network, 79 sources in total were defined. With the least number of documents and citations for each source was set at 2 and 1, respectively, with 38 sources meeting these criteria contained in the source network of main outlets. The network also presents the information flow between nodes, which indicates the citation strength of the data. The tightness of links and the size of nodes suggest the relative impact of the node and the intensity of their respective connections [46].

According to the network shown in Figure 3, the most frequently cited journal in this collection is "*Automation in Construction*," which was identified as the most effective channel on this topic. From the arrow directions in this network, the information flow begins with "Automation in Construction" as a source of citations. The published papers in this journal generally are based on the researches focusing on technology, software, integrated technologies, and automation. This reveals the fact that the effective outlets hitherto are highly technology oriented, while journals focusing on professional issues, management, construction, and education are less influential in terms of the integration in BIM. Just as contended that the BIM study is almost entirely driven from the perspective of technology.

As a result, available researches, technology oriented on researches into BIM, have not addressed project management and managerial features of integration. These findings point out that enhancing integration in BbCNs is still considered as a technical matter, despite that researchers increasingly value the key role of managerial components in BbCNs.

To comprehend the contents mentioned in researches connected with integration in BbCNs, the cooccurrence network of keywords was established from the dataset containing 90 documents. "Authors keywords" rather than all keywords were applied to create visualization. The method of "fractional counting" allowed us to extract 454 keywords from the dataset. The least occurrence number of keywords is set at 5, and it resulted in a cooccurrence network of 51 terms with 178 links. As Lee and Yu [20] said, the author keywords present the core of the research, and the key point of the survey was selected by authors carefully. Therefore, the cooccurrence network of keywords shown in Figure 4 demonstrates the highlights of research covered by the literature included in the dataset.

The idea of the PageRank algorithm originates from the mechanism of citation indexing. The more the papers are cited by the more authoritative papers, the more valuable these papers are. This algorithm allows us to rank the nodes based on their importance in the network. From the distance between the nodes and the strength of those links (Figure 4), it is seen that everything highlighted here is BIM or expansions of BIM, while integration was found to be associated only with the node of *benchmark*, *construction, and information technologies*. The size of the node also represents the degree of recognition, abd the results drawn

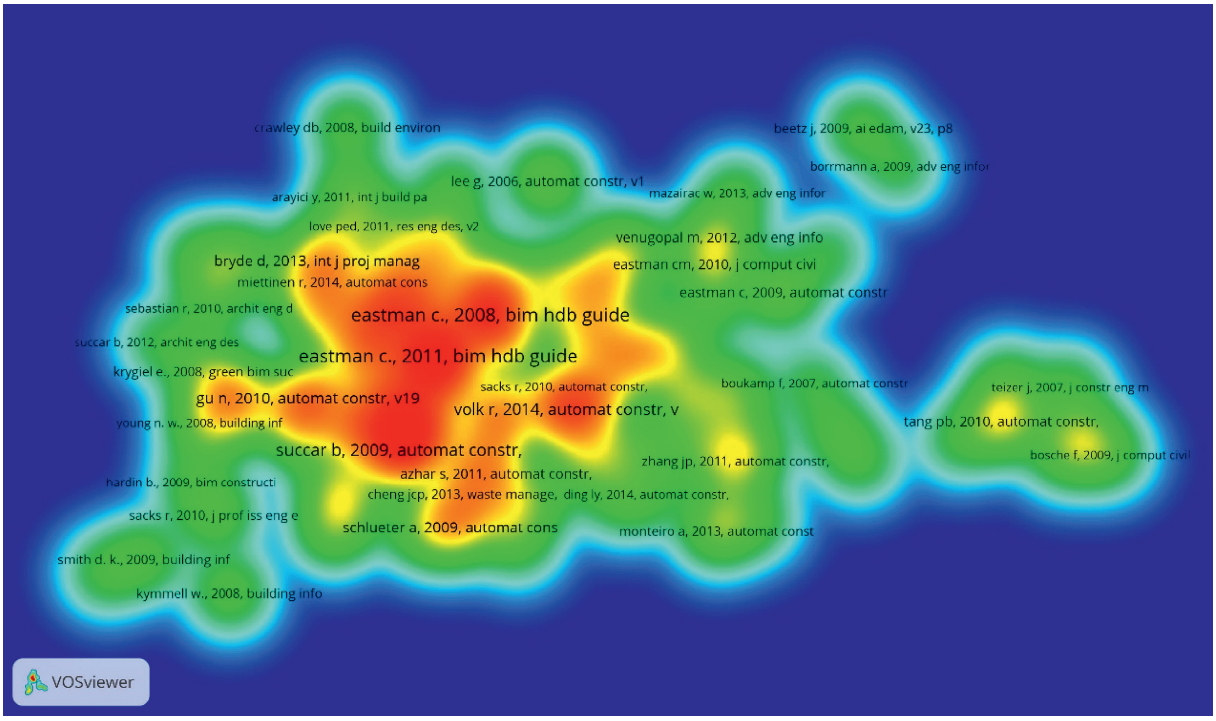


Figure 2: Most influential studies in BIM field: 2008–2018.

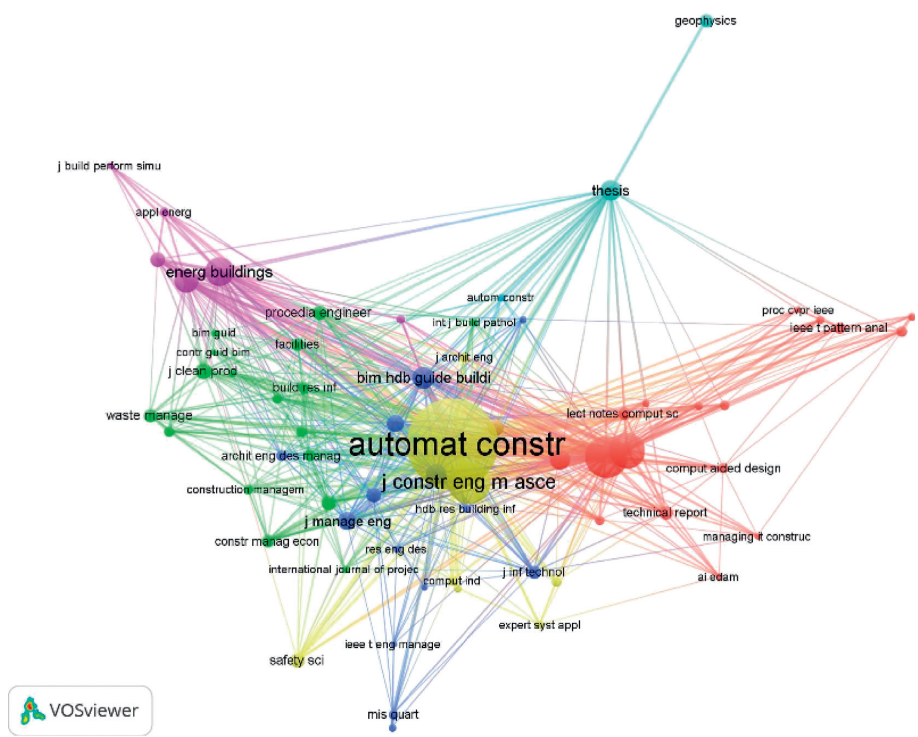


Figure 3: The main outlet networks describing the "*Automation in Construction*" as the most effective journal on the topic of integration in BbCNs.

from Figure 4 stated that technology-oriented studies received much more attention than those focusing on integration.

Accordingly, the author keywords' cooccurrence network confirms the discovery of the relevant outlets, and integration is hardly resolved from PM perspective within the body of knowledge on integration in BbCNs. This conclusion is made from the absence of a direct links between the two nodes and the distance between those nodes on the network as shown in Figure 4.

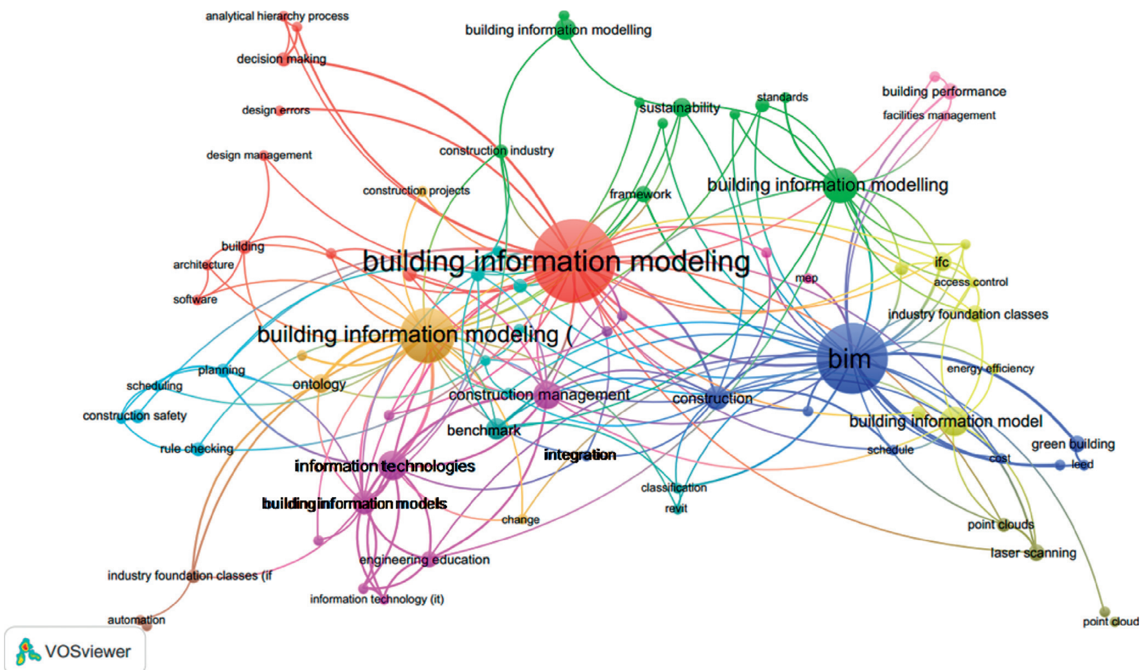


Figure 4: The cooccurrence network of keywords for the studies on integration in BbCNs describing the nodes of *benchmark*, *construction, and information technologies* closely related to *integration*.

3.2. Qualitative Analysis of the Literatures Associated with Integration in BbCNs. To reduce the scope of the dataset and recognize researches relevant to integration directly, all 90 recognized documents have been reviewed to discover their major points. Each study has thoroughly been reviewed upon "*integration pentagon*" by at least two times to determine their relevance with the integration in BbCNs. A total of 42 articles were identified and covered in qualitative analysis shown in Table 1.

As affirmed by Abbas et al. [55], "coding is the beginning form in any kind of qualitative analysis, and also the basis of the later." One forward-thinking method of coding is to concentrate on the contrast, similarity, and comparison with an existing model or framework to frame the corresponding explanation [40]. In this study, the coding list of the all 42 articles is made on the basis of the *integration pentagon* as illustrated in Figure 1. The researches reviewed all 42 articles and allocated the content to the codes presented in Figure 1. The classification results of the content is shown in Table 1, which clearly illustrates the focus of the selected literatures and allows researchers to spot the differences easily.

3.3. Context Dimension of Integration in BbCNs. Eight studies (20% of the total) focus on the context dimension in influencing the integration in BbCNs, registering the highest rate among all dimensions in this review. Context dimension refers to the environment conducive to the development of integration in BbCNs. It is necessary to provide a fertile soil for plant growth; likewise, it is important to nurture a supportive environment to enhance integration in BbCNs [5, 53]. In this sense, the focus of the articles highlighting "context" dimension is to identify the major driving forces to nurture a supportive environment [38].

Grilo and Jardim-Goncalves [27], Fadeyi [54], Jacobsson and Linderoth [49], and Demirkesen and Ozorhon [12] brought to light the central role of an encouraging organizational environment good for integration, affecting BbCNs as socio-organizational factors. Studies falling in this category also figured out a favorable context to develop the integration in BbCNs, including improving BIM education [55], exerting positive influence from the culture [49], and building up a needed legal framework to consummate the organizational environment. Accordingly, three key barriers to integration are the concept, and knowledge of interorganizational integration is the key skill that should be incorporated into the BIM education programs [55]. In addition, resisting the change from traditional work practices, adapting to innovative technologies, takes a long time, lacking understanding of the processes and workflows required by BIM [28, 56, 76, 77].

By studying the existing researches, we can get the enlightenment that the key work of cultivating a supportive environment to enhance integration in BbCNs lies in transforming the traditional thinking patterns of organizational division of labor. The impact of education and policy laws accelerates the shift by making the participants in BbCNs realize that the integration and BIM are more than just a tool, but an important innovation of organizational model is driven by a multiwin business strategy. In future researches, more attention should be attached to the strategies and mechanisms promoting the transformation of thinking patterns.

Table 1: Study associated with integration in BbCNs and the dimensions targeted in each study.

ID	Study associated with integration in BbCNs	Dimensions of integration pentagon
1	Akintola et al. [47]	Actor
2	Demirkesen and Ozorhon [12]	Actor/context
3	Habibi [48]	Actor
4	Jacobsson and Linderoth [49]	Actor/context
5	Linderoth [13]	Actor
6	Ozorhon et al. [50]	Actor
7	Rahman et al. [51]	Actor
8	Shao [52]	Actor
9	Poirier et al. [53]	Context
10	Liu et al. [5]	Context/process
11	Fadeyi [54]	Context
12	Abbas et al. [55]	Context
13	Grilo and Jardim-Goncalves [27]	Context/process
14	Babič et al. [56]	Context
15	Gemünden et al. [57]	Organization
16	Eskerod and Larsen [58]	Organization
17	Wen and Qiang [59]	Organization/task
18	Oti et al. [60]	Organization
19	Mignone et al. [61]	Organization
20	Al Mousli and El-Sayegh [17]	Organization
21	Son et al. [62]	Organization
22	Berteaux and Javernick-Will [30]	Organization
23	Whyte and Hartmann [63]	Organization
24	Ajam et al. [64]	Organization/process
25	Solihin et al. [23]	Process
26	Dave et al. [65]	Process
27	Ahola et al. [11]	Process
28	Ilhan and Yaman [66]	Process
29	Forgues et al. [67]	Process
30	Amann and Borrmann [45]	Process
31	Tarandi [68]	Process
32	Arayici et al. [69]	Process
33	Zhang et al. [70]	Process
33	Wang et al. [29]	Process
34	Ding et al. [71]	Process
35	Yi et al. [6]	Process
36	London and Singh [72]	Process
37	Chen et al. [18]	Process/task
38	Sanguinetti et al. [73]	Process
39	Singh et al. [74]	Process
40	Gassel et al. [19]	Task
41	Papadonikolaki et al. [2]	Task
42	Shin [75]	Task

3.4. Actor Dimension of Integration in BbCNs. Implementation of a new technology inevitably leads to the emergence of new work roles of the individual team members [39]. As Azhar [78] said, BIM represents a new paradigm within AEC, one that encourages integration of the roles of all stakeholders on a project. As illustrated in Table 1, 8 studies (20%) focus on the roles of BbCN actor. These studies in this category show that the present organizational actors were not supportive of the concomitant process changes associated with new technological solutions [79] because in effect, the changes intrinsic to BIM implementation is substantial and it necessitates new set of skills and new ways of thinking.

Consequently, the roles of BbCNs, which are relevant for supporting BbCNs-enabled project, have been identified: include not only technical competencies bus also skills related to process changes and management [47, 48, 51]. Concerning expectations of the characteristics of a BbCNs actor, these researches had relatively similar opinions that are made in these researches. Besides, there seems a high expectation on the characteristics of a BbCNs actor, especially in terms of excellent interpersonal skills, commitment, and leadership in the study of Jacobsson and Linderoth [49] and Linderoth [13]. Bosch-Sijtsema et al. [80] and Shao [52] compared the similarities and significant differences between BIM and non-BIM actors in characteristics, experiences, and education and found that BIM actors considered their roles, characteristics, and education as coordinating and pushing for change.

In conclusion, we find that the data from these studies provide insights into the level of professional competence of the BbCNs actor. Nevertheless, there has been scant research on the responsibilities and obligations of BbCN-related roles. Given present incomplete researches, one might conclude that a systematic study on the topic of the BbCNs actor is of necessity.

3.5. Process Dimension of Integration in BbCNs. As shown in Table 1, 18 studies explore the importance of process on integration in BbCNs. This subsystem involves business processes and the technologies (tools, techniques, machines, etc.) with functionalities to perform required processes and enhance the overall performance of the system [71, 72, 74]. Studies falling in this category such as Uhm et al. [81], Liu et al. [5], Takim et al. [82], and Succar [83] underline the use of software and tools as required processes to support integration in BbCNs.

Solihin et al. [23] proposed a framework that can more fully integrate different models into an integrated model in a federated environment. Liu et al. [5] stated that the reliable network-based systems are conducive to achieving successful integration. Amann and Borrmann [45], Ajam et al. [64], Sanguinetti et al. [73], and Yi et al. [6] identified that cloud-based platforms are of a great potential for integrating models, simulating components, and providing seamless data sharing for end users in BbCNs. Ahola et al. [11] and Arayici et al. [69] proposed an interoperability specification development approach for intergraded BIM use in performance-based design. Zhang et al. [70], Dave et al. [65], and Ilhan and Yaman [66] also proposed a multiserver information sharing with a private cloud after analyzing the requirements for cross-party integration in a BIM scenario.

Scholars, however, came upon different points of view. Just as what has been described by Grilo et al. [84], process integration cannot be simply regarded as a result of cloud-based tools and coordination and collaboration among stakeholders are equally important. In terms of this arguments, we propose that the follow-up researches into process integration should focus on both technology and management perspectives.

3.6. Organization Dimension of Integration in BbCNs. Following the presentation in Table 1, 10 studies stress the importance of organization on integration in BbCNs. Organizational dimension is to integrate a set of participants with different functions into an organic organization. Arayici et al. [69] stated that the problem of interoperability between organizations exists in many areas where collaboration, interaction, and data exchange are required. This is especially suitable for the construction, engineering and construction (AEC) fields, where the evolution of practice and the BIM paradigm have reinforced the need for integration among different stakeholders.

Whyte and Hartmann [63], Gemünden et al. [57], and Oti et al. [60] found that BIM become a "cultural driver" for integration, and each partner in the BIM-enabled project will bring new aspects to the project organization, which will require organization changes in how BIM is applied and used. The findings present in the literature work in this category suggest that the redefining work roles [9, 85] and designing relationships [30] have been considered as positive factors to support organizational integration. In addition, some scholars have proposed that establishing the mechanism of benefit conforming and contradiction handling contribute to can effectively improve the level of trust and then promote the cooperation of participants [17, 59, 61].

Building on the discussions above, the future research on organization dimension is expected: (1) investigate the contract forms of BbCNs, (2) identify the supportive organizational structures, and (3) follow a multisystem thinking of a governance model.

3.7. Task Dimension of Integration in BbCNs. As inferred from Table 1, 5 studies explore integration from microperspective, focusing on the importance of tasks on integration in BbCNs. In these studies, discussions are made on the potential impact of tasks performed by a BbCNs and how they influence team functioning and effectiveness [75, 81]. An interesting result is that seemingly low volume of papers addresses the *actor* aspect of BbCNs, this being referred to as one of the best aspects of BbCNs, though.

Literatures in this category attach important specific tasks and activities of integration in BbCNs, such as integrated knowledge, integrated changes, and integrated production factors. As illustrated by Chen et al. [18], Xue et al. [77], and Wen and Qiang [59], integrated knowledge is definitely essential for fulfilling integration in BbCNs. This is because knowledge disclosure would result in repetitive work and waste, lack of innovation and thus leads to organization inefficiency. The studies by Gassel et al. [19] proved that the integration of changes lends to fewer obstacle for information transmission and less time for information interaction between participants, thus making the change more time sensitive. The findings also indicate that BbCNs could not only support the project development process as a systematic management tool but also serve as a core data generator and platform allowing other participants to perform further tasks.

Generally, previous researchers into task dimension highlight the tasks required to implement BbCNs, yet with insufficient details, i.e., there shows a lack of more detailed research. Such as a lack of research on how task types and task complexity influence the performance of BbCNs implementation.

4. Implications of the Findings

Identifying further strategies for BbCNs is an intriguing area for future research. Based on the scientmetric analysis, some fundamental viewpoints and frontier insights with respect to the existing literatures into integration in BbCNs have been developed. Systematic mixed-methods allow us to review the available literatures on BIM, and the result suggests that integration is a core element in the BIM literature. Although the potential value of integration in advancing successful BIM-based projects have been accepted [9], the research into integration in BbCNs has not received enough attention it deserves (Figure 2). The findings also show that previous studies mainly explored integration in BbCNs from a technology-oriented orientation (Figure 3). Although BIM is a sociotechnical system [5], the research into BIM has not been carried out from the managerial perspective, and deficient focus has been made on social-related features of integration within BbCNs [9]. Such a research situation runs counter to the widely held view in the industrial sector that "successful integration originates from 80% of people and 20% of the technology or information." It shows that the future research into integration in BbCNs must shift the focus to the managerial areas.

To reach the study objective, a qualitative analysis based on *integration pentagon* is conducted to exam and demonstrate the current status and future directions of integration in BbCNs. The findings call for future research to target these dimensions such as context, tasks, actors, and organization, which are currently under-represented in studies exploring integration in BbCNs. The findings magnified the gap in the study of *context* dimension so that future research is expected to cultivate the incentive mechanism for promoting the enthusiasm of participants to implement BbCNs in project management practice. The research gaps related to the *actor* dimension call for a systematic research to identify the responsibilities and obligations of BbCNs-related roles. As for the *organization* dimension, three components including the contract forms of BbCNs, a multisystem thinking of the governance model, and the supportive organizational structures should receive attention. The challenge the existing studies of *task* dimension confronts is that implementing BbCNs often requires a specific environment, so the future research in this regard must be highly bespoke and context specific. In other words, future research on task dimension should take into account its interrelationships with organizational context, structures, roles, and other elements.

In addition, the outcome of this study also reveals that existing BIM researches explore integration from a fragmented and disjointed way. Namely, isolated antecedents are observed in various researches with little paying no attention to the importance of associations and the synergy between these antecedents. These antecedents' dimensions of integration in BbCNs have rarely been considered as necessary components of a unified system. There is a lack of necessary attention to reflect how the integration is affected by misalignment between these dimensions. Even if Leavitt had earlier argued for the interrelatedness of these sociotechnical system dimensions and for the need for Aa comprehensive consideration. These conclusions consequently lead to a call for more studies that examine the interacting impacts and synergy among the interrelated integration dimensions in BbCNs.

5. Conclusions and Future Research

Although enhancing integration in BbCNs has been a well-recognized problem, this study explores the problem in an all-round way. This study has drawn findings from a batch of literature works comprising 42 studies. A systematic mixed-method review was used to analyze the storyline of research studies relevant to integration in BbCNs. The results provide a solid foundation for the research of integration in BbCNs. Moreover, this study also extends the scope of research into integration in BbCNs by focusing on the significance of social components. The primary theoretical and methodological contribution made by this study to the body of knowledge of integration in BbCNs can be summed up in three aspects.

First, this study maps a research area of integration in BbCNs based on the knowledge base, domains, and evolution by using a systematic mixed-method review. The study results highlight how the research of integration of BbCNs evolves, thus greatly contributing to understanding the status quo of BIM knowledge. The methods presented detailed in this study can be generalized and used as an effective tool for mapping discipline knowledge. It is recommended that future studies should be conducted periodically to improve the BOK of BbCNs provided in this study.

Second, in this study, an extended Leavitt sociological model was used for reference to build an *integration pentagon* which was made up of context, process, organization, task and actor. The *integration pentagon* is used as the conceptualization theoretical lens offering researchers to identify the existing gaps in the literature regarding the integration in BbCNs and providing a theoretical foundation to test and guide future research. The *integration pentagon* also enhances our comprehension of the integration antecedents for BbCNs by emphasizing the essentiality of pondering these enablers from an all in view.

More importantly, these findings provide a valuable reference to the developers of BbCNs to understand the major barriers in their decision-making and to government aiming at promoting BIM or BbCNs in the construction industry with relevant policies and incentives.

Despite that the contributions of this study have been mentioned, some of the study limitations must be acknowledged before applying the findings. First, the research is made merely based on WoS publications. Another limitation involves generalization, which is a result of using specific keywords which may omit the relevant research. In addition, the *integration pentagon*, which has been used to match and encode studies on integration, could be considered subjective in nature. In future studies, this may occur by incorporating members to check validation processes to enhance the credibility. In addition, a lack of publications in available databases also affected the results of bibliometric analysis.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] R. Jin, C. M. Hancock, L. Tang, and D. Wanatowski, "BIM investment, returns, and risks in China's AEC industries," *Journal of Construction Engineering and Management*, vol. 143, no. 12, article 04017089, 2017.

[2] E. Papadonikolaki, R. Vrijhoef, and H. Wamelink, "The interdependences of BIM and supply chain partnering: empirical explorations," *Architectural Engineering & Design Management*, vol. 12, no. 6, pp. 476–494, 2016.

[3] A. Grilo and R. Jardim-Goncalves, "Cloud-marketplaces: distributed e-procurement for the AEC sector," *Advanced Engineering Informatics*, vol. 27, no. 2, pp. 160–172, 2013.

[4] D. Cao, H. Li, G. Wang, and T. Huang, "Identifying and contextualising the motivations for BIM implementation in construction projects: an empirical study in China," *International Journal of Project Management*, vol. 35, no. 4, pp. 658–669, 2017.

[5] Y. Liu, S. van Nederveen, and M. Hertogh, "Understanding effects of BIM on collaborative design and construction: an empirical study in China," *International Journal of Project Management*, vol. 35, no. 4, pp. 686–698, 2017.

[6] J. Yi, Y. Wang, S. Zhang, L. Yin, B. Yang, and Y. Lei, "A cloud approach to unified lifecycle data management in architecture, engineering, construction and facilities management: integrating BIMs and SNS," *Advanced Engineering Informatics*, vol. 27, no. 2, pp. 173–188, 2013.

[7] M. T. Shafiq, J. Matthews, and S. R. Lockley, "A study of BIM collaboration requirements and available features in existing model collaboration systems," *Journal of Information Technology in Construction*, vol. 18, pp. 148–161, 2013.

[8] E. Alreshidi, M. Mourshed, and Y. Rezgui, "Requirements for cloud-based BIM governance solutions to facilitate team collaboration in construction projects," *Requirements Engineering*, vol. 23, no. 1, pp. 1–31, 2016.

[9] H. M. Reza, B. Saeed, C. Nicholas et al., "BIM adoption within Australian small and medium-sized enterprises (SMEs): an innovation diffusion model," *Construction Economics and Building*, vol. 16, no. 3, pp. 71–86, 2016.

[10] M. Oraee, M. R. Hosseini, E. Papadonikolaki, R. Palliyaguru, and M. Arashpour, "Collaboration in BIM-based construction networks: a bibliometric-qualitative literature review," *International Journal of Project Management*, vol. 35, no. 7, pp. 1288–1301, 2017.

[11] T. Ahola, M. Vuori, and E. Viitamo, "Sharing the burden of integration: an activity-based view to integrated solutions provisioning," *International Journal of Project Management*, vol. 35, no. 6, pp. 1006–1021, 2017.

[12] S. Demirkesen and B. Ozorhon, "Impact of integration management on construction project management performance," *International Journal of Project Management*, vol. 35, no. 8, pp. 1639–1654, 2017.

[13] H. C. J. Linderoth, "Understanding adoption and use of BIM as the creation of actor networks," *Automation in Construction*, vol. 19, no. 1, pp. 66–72, 2010.

[14] M. Löwstedt, C. Räisänen, and R. Leiringer, "Doing strategy in project-based organizations: actors and patterns of action," *International Journal of Project Management*, vol. 36, no. 6, pp. 889–898, 2018.

[15] C. Merschbrock, M. R. Hosseini, I. Martek, M. Arashpour, and G. Mignone, "Collaborative role of sociotechnical components in BIM-based construction networks in two hospitals," *Journal of Management in Engineering*, vol. 34, no. 4, article 05018006, 2018.

[16] R. M. Dowsett and C. F. Harty, "Assessing the implementation of BIM—an information systems approach," *Construction Management and Economics*, pp. 1–16, 2018.

[17] M. H. Al Mousli and S. M. El-Sayegh, "Assessment of the design—construction interface problems in the UAE," *Architectural Engineering and Design Management*, vol. 12, no. 5, pp. 353–366, 2016.

[18] S. M. Chen, F. H. Griffis, P. H. Chen, and L. M. Chang, "A framework for an automated and integrated project scheduling and management system," *Automation in Construction*, vol. 35, no. 11, pp. 89–110, 2013.

[19] F. J. M. V. Gassel, T. Láscaris-Comneno, and G. J. Maas, "The conditions for successful automated collaboration in construction," *Automation in Construction*, vol. 39, pp. 85–92, 2014.

[20] S. K. Lee and J. H. Yu, "Success model of project management information system in construction," *Automation in Construction*, vol. 25, pp. 82–93, 2012.

[21] E. Papadonikolaki and H. Wamelink, "Inter- and intra-organizational conditions for supply chain integration with BIM," *Building Research & Information the International Journal of Research Development & Demonstration*, vol. 45, no. 1, pp. 1–16, 2017.

[22] J. Whyte, A. Stasis, and C. Lindkvist, "Managing change in the delivery of complex projects: configuration management, asset information and "big data"," *International Journal of Project Management*, vol. 34, no. 2, pp. 339–351, 2016.

[23] W. Solihin, C. Eastman, and Y. Lee, "A framework for fully integrated building information models in a federated environment," *Advanced Engineering Informatics*, vol. 30, no. 2, pp. 168–189, 2016.

[24] T. R. Browning, "Managing complex project process models with a process architecture framework," *International Journal of Project Management*, vol. 32, no. 2, pp. 229–241, 2014.

[25] A. Butt, M. Naaranoja, and J. Savolainen, "Project change stakeholder communication," *International Journal of Project Management*, vol. 34, no. 8, pp. 1579–1595, 2016.

[26] D. Gough, "Qualitative and mixed methods in systematic reviews," *Systematic Reviews*, vol. 4, no. 1, pp. 1–3, 2015.

[27] A. Grilo and R. Jardim-Goncalves, "Value proposition on interoperability of BIM and collaborative working environments," *Automation in Construction*, vol. 19, no. 5, pp. 522–530, 2010.

[28] R. Eadie, M. Browne, H. Odeyinka, C. McKeown, and S. McNiff, "A survey of current status of and perceived changes required for BIM adoption in the UK," *Built Environment Project and Asset Management*, vol. 5, no. 1, pp. 4–21, 2015.

[29] W. C. Wang, S. W. Weng, S. H. Wang, and C. Y. Chen, "Integrating building information models with construction process simulations for project scheduling support," *Automation in Construction*, vol. 37, no. 6, pp. 68–80, 2014.

[30] F. Berteaux and A. Javernick-Will, "Adaptation and integration for multinational project-based organizations," *Journal of Management in Engineering*, vol. 31, no. 6, article 04015008, 2015.

[31] M. Gibbert, W. Ruigrok, and B. Wicki, "What passes as a rigorous case study?," *Strategic Management Journal*, vol. 29, no. 13, pp. 1465–1474, 2008.

[32] R. P. Bostrom, S. Gupta, and D. Thomas, "A meta-theory for understanding information systems within sociotechnical systems," *Journal of Management Information Systems*, vol. 26, no. 1, pp. 17–48, 2009.

[33] S. Alter, "The work system method for understanding information systems and information systems research," *Communications of the Association for Information Systems*, vol. 9, 2002.

[34] H.-J. Bargstädt, "Challenges of BIM for construction site operations," *Procedia Engineering*, vol. 117, pp. 52–59, 2015.

[35] E. Sackey, M. Tuuli, and A. Dainty, "Sociotechnical systems approach to BIM implementation in a multidisciplinary construction context," *Journal of Management in Engineering*, vol. 31, no. 1, article A4014005, 2015.

[36] H. J. Leavitt, "Applied organization change in industry: structural, technical and human approaches," *Experimental Brain Research*, vol. 45, no. 1-2, pp. 1–12, 1964.

[37] K. Davis, "Different stakeholder groups and their perceptions of project success," *International Journal of Project Management*, vol. 32, no. 2, pp. 189–201, 2014.

[38] E. Poirier, D. Forgues, and S. Staub-French, "Collaboration through innovation: implications for expertise in the AEC sector," *Construction Management and Economics*, vol. 34, no. 11, pp. 769–789, 2016.

[39] Q. He, G. Wang, L. Luo, Q. Shi, J. Xie, and X. Meng, "Mapping the managerial areas of Building information modeling (BIM) using scientometric analysis," *International Journal of Project Management*, vol. 35, no. 4, pp. 670–685, 2017.

[40] K. Lyytinen and M. Newman, "Explaining information systems change: a punctuated socio-technical change model," *European Journal of Information Systems*, vol. 17, no. 6, pp. 589–613, 2008.

[41] W. Aarseth, T. Ahola, K. Aaltonen, A. Økland, and B. Andersen, "Project sustainability strategies: a systematic literature review," *International Journal of Project Management*, vol. 35, no. 6, pp. 1071–1083, 2017.

[42] C. Ke, W. Lu, P. Yi, S. Rowlinson, and G. Q. Huang, "Bridging BIM and building: from a literature review to an integrated conceptual framework," *International Journal of Project Management*, vol. 33, no. 6, pp. 1405–1416, 2015.

[43] N. J. V. Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping," *Scientometrics*, vol. 84, no. 2, pp. 523–538, 2010.

[44] A. M. Mahamadu, L. Mahdjoubi, and C. Booth, "Challenges to BIM-cloud integration: implication of security issues on secure collaboration," *Journal of Endocrinological Investigation*, vol. 28, no. 7, pp. 425–431, 2013.

[45] J. Amann and A. Borrmann, "Embedding procedural knowledge into building information models: the IFC procedural language and its application for flexible transition curve representation," *Journal of Computing in Civil Engineering*, vol. 30, no. 5, article C4016006, 2016.

[46] Z. Riaz, M. Arslan, A. K. Kiani, and S. Azhar, "CoSMoS: a BIM and wireless sensor based integrated solution for worker safety in confined spaces," *Automation in Construction*, vol. 45, pp. 96–106, 2014.

[47] A. Akintola, S. Venkatachalam, and D. Root, "New BIM roles' legitimacy and changing power dynamics on BIM-enabled projects," *Journal of Construction Engineering and Management*, vol. 143, no. 9, article 04017066, 2017.

[48] S. Habibi, "The promise of BIM for improving building performance," *Energy and Buildings*, vol. 153, pp. 525–548, 2017.

[49] M. Jacobsson and H. C. J. Linderoth, "The influence of contextual elements, actors' frames of reference, and technology on the adoption and use of ICT in construction projects: a Swedish case study," *Construction Management & Economics*, vol. 28, no. 1, pp. 13–23, 2010.

[50] B. Ozorhon, C. Abbott, and G. Aouad, "Integration and leadership as enablers of innovation in construction: case study," *Journal of Management in Engineering*, vol. 30, no. 2, pp. 256–263, 2014.

[51] R. A. Rahman, S. Alsafouri, P. Tang, and S. K. Ayer, "Comparing building information modeling skills of project managers and BIM managers based on social media analysis," *Procedia Engineering*, vol. 145, pp. 812–819, 2016.

[52] J. Shao, "The moderating effect of program context on the relationship between program managers' leadership competences and program success," *International Journal of Project Management*, vol. 36, no. 1, pp. 108–120, 2018.

[53] E. A. Poirier, D. Forgues, and S. Staubfrench, "Understanding the impact of BIM on collaboration: a Canadian case study," *Building Research & Information*, vol. 45, no. 6, pp. 681–695, 2017.

[54] M. O. Fadeyi, "The role of building information modeling (BIM) in delivering the sustainable building value," *International Journal of Sustainable Built Environment*, vol. 6, no. 2, pp. 711–722, 2017.

[55] A. Abbas, Z. U. Din, and R. Farooqui, "Integration of BIM in construction management education: an overview of Pakistani engineering universities," *Procedia Engineering*, vol. 145, pp. 151–157, 2016.

[56] N. Č. Babič, P. Podbreznik, and D. Rebolj, "Integrating resource production and construction using BIM," *Automation in Construction*, vol. 19, no. 5, pp. 539–543, 2010.

[57] H. G. Gemünden, P. Lehner, and A. Kock, "The project-oriented organization and its contribution to innovation," *International Journal of Project Management*, vol. 36, no. 1, pp. 147–160, 2018.

[58] P. Eskerod and T. Larsen, "Advancing project stakeholder analysis by the concept "shadows of the context"," *International Journal of Project Management*, vol. 36, no. 1, pp. 161–169, 2018.

[59] Q. Wen and M. Qiang, "Coordination and knowledge sharing in construction project-based organization: a longitudinal structural equation model analysis," *Automation in Construction*, vol. 72, pp. 309–320, 2016.

[60] A. H. Oti, W. Tizani, F. H. Abanda, A. Jaly-Zada, and J. H. M. Tah, "Structural sustainability appraisal in BIM," *Automation in Construction*, vol. 69, pp. 44–58, 2016.

[61] G. Mignone, M. R. Hosseini, N. Chileshe, and M. Arashpour, "Enhancing collaboration in BIM-based construction networks through organisational discontinuity theory: a case study of the new Royal Adelaide Hospital," *Architectural Engineering & Design Management*, vol. 12, no. 5, pp. 333–352, 2016.

[62] H. Son, S. Lee, and C. Kim, "What drives the adoption of building information modeling in design organizations? An empirical investigation of the antecedents affecting architects' behavioral intentions," *Automation in Construction*, vol. 49, no. 8, pp. 92–99, 2015.

[63] J. K. Whyte and T. Hartmann, "How digitizing building information transforms the built environment," *Building Research & Information*, vol. 45, no. 6, pp. 591–595, 2017.

[64] M. Ajam, M. Alshawi, and T. Mezher, "Augmented process model for e-tendering: towards integrating object models with document management systems," *Automation in Construction*, vol. 19, no. 6, pp. 762–778, 2010.

[65] B. Dave, A. Buda, A. Nurminen, and K. Främling, "A framework for integrating BIM and IoT through open standards," *Automation in Construction*, vol. 95, pp. 35–45, 2018.

[66] B. Ilhan and H. Yaman, "Green building assessment tool (GBAT) for integrated BIM-based design decisions," *Automation in Construction*, vol. 70, pp. 26–37, 2016.

[67] E. C. Forgues, V. Carignan, D. Forgues, and S. B. Rajeb, "A framework for improving collaboration patterns in BIM projects," in *Proceedings of the International Conference on Cooperative Design*, Sydney, Australia, October 2016.

[68] V. Tarandi, "A BIM collaboration lab for improved through life support," *Procedia Economics & Finance*, vol. 21, pp. 383–390, 2015.

[69] Y. Arayici, T. Fernando, V. Munoz, and M. Bassanino, "Interoperability specification development for integrated BIM use in performance based design," *Automation in Construction*, vol. 85, pp. 167–181, 2018.

[70] J. Zhang, Q. Liu, Z. Hu, J. Lin, and F. Yu, "A multi-server information-sharing environment for cross-party collaboration on a private cloud," *Automation in Construction*, vol. 81, pp. 180–195, 2017.

[71] L. Ding, Y. Zhou, and B. Akinci, "Building information modeling (BIM) application framework: the process of expanding from 3D to computable nD," *Automation in Construction*, vol. 46, pp. 82–93, 2014.

[72] K. London and V. Singh, "Integrated construction supply chain design and delivery solutions," *Architectural Engineering and Design Management*, vol. 9, no. 3, pp. 135–157, 2013.

[73] P. Sanguinetti, S. Abdelmohsen, J. M. Lee, J. K. Lee, H. Sheward, and C. Eastman, "General system architecture for BIM: an integrated approach for design and analysis," *Advanced Engineering Informatics*, vol. 26, no. 2, pp. 317–333, 2012.

[74] V. Singh, N. Gu, and X. Wang, "A theoretical framework of a BIM-based multi-disciplinary collaboration platform," *Automation in Construction*, vol. 20, no. 2, pp. 134–144, 2011.

[75] T.-S. Shin, "Building information modeling (BIM) collaboration from the structural engineering perspective," *International Journal of Steel Structures*, vol. 17, no. 1, pp. 205–214, 2017.

[76] A. Porwal and K. N. Hewage, "Building information modeling (BIM) partnering framework for public construction projects," *Automation in Construction*, vol. 31, pp. 204–214, 2013.

[77] X. Xue, Q. Shen, and Z. Ren, "Critical review of collaborative working in construction projects: business environment and human behaviors," *Journal of Management in Engineering*, vol. 26, no. 4, pp. 196–208, 2010.

[78] S. Azhar, "Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry,"

Leadership & Management in Engineering, vol. 11, no. 3, pp. 241–252, 2011.

[79] R. Sebastian, "Changing roles of the clients, architects and contractors through BIM," *Engineering Construction & Architectural Management*, vol. 18, no. 2, pp. 176–187, 2011.

[80] P. M. Bosch-Sijtsema, P. Gluch, and A. A. Sezer, "Professional development of the BIM actor role," *Automation in Construction*, vol. 97, pp. 44–51, 2019.

[81] M. Uhm, G. Lee, and B. Jeon, "An analysis of BIM jobs and competencies based on the use of terms in the industry," *Automation in Construction*, vol. 81, pp. 67–98, 2017.

[82] R. Takim, M. Harris, and A. H. Nawawi, "Building information modeling (BIM): a new paradigm for quality of life within architectural, engineering and construction (AEC) industry," *Procedia—Social and Behavioral Sciences*, vol. 101, pp. 23–32, 2013.

[83] B. Succar, "Building information modelling framework: a research and delivery foundation for industry stakeholders," *Automation in Construction*, vol. 18, no. 3, pp. 357–375, 2009.

[84] A. Grilo, A. Zutshi, R. Jardim-Goncalves, and A. Steiger-Garcao, "Construction collaborative networks: the case study of a building information modelling-based office building project," *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 1-2, pp. 152–165, 2013.

[85] O. Salem, J. Solomon, A. Genaidy, and I. Minkarah, "Lean construction: from theory to implementation," *Journal of Management in Engineering*, vol. 22, no. 4, pp. 168–175, 2006.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 3720191, 13 pages
https://doi.org/10.1155/2019/3720191

Research Article

A BIM-Based Study on the Comprehensive Benefit Analysis for Prefabricated Building Projects in China

Yingbo Ji,[1] Siwei Chang ,[1] Yuan Qi,[1] Yan Li,[2] Hong Xian Li ,[2] and Kai Qi[1]

[1]*School of Civil Engineering, North China University of Technology, Beijing 100043, China*
[2]*School of Architecture and Built Environment, Deakin University, Geelong 3220, Australia*

Correspondence should be addressed to Siwei Chang; siwei_chang@126.com

Received 27 January 2019; Revised 22 March 2019; Accepted 2 April 2019; Published 2 May 2019

Guest Editor: Eugenio Pellicer

Prefabricated construction has been widely accepted as an alternative to conventional cast-in-situ construction, given its improved performance. Great efforts have also been made to develop prefabricated construction technologies in China. However, there is a lack of an appropriate pattern for evaluating its comprehensive economic merits, and reasonable mathematical models for providing a comparative analysis of conventional cast-in-situ and prefabricated building projects have yet to be developed. Therefore, the research in this paper aims to comprehensively evaluate the economic benefits of implementing prefabricated construction techniques in order to surpass the economic barrier and promote the development of prefabricated buildings in China. The comprehensive economic evaluation is formulated in terms of resource-use efficiencies, project progress, and incentive policies. An apartment building in Shanghai is selected as a case study. Construction progress is simulated on the BIM platform when the same case study is rationally transformed from the prefabricated to the conventional cast-in-situ construction technique. The results reveal that the comprehensive economic merit can reach ¥739.6/m^2 when selecting the prefabricated construction process. The economic benefit brought by shortening the construction period can be regarded as the most significant contributor. Yet, the current incentive policies only contribute 7.1% of the comprehensive economic evaluation. Overall, this research contributes an assessment framework for decision-making in the technique management of building construction. The BIM-based simulation approach can greatly help investors to identify the relevant economic factors and adopt the latest incentive policies.

1. Introduction

The adoption of new technological advancement in the construction industry plays an important role in achieving project success. For example, prefabrication technology has been widely practiced in many countries and has fostered substantial change in the development of the construction industry worldwide in recent decades [1, 2]. Prefabricated construction refers to the practice of designing and fabricating building elements in manufacturing factories, transporting the elements to construction sites, and assembling the elements to a greater degree of finish for rapid site assembly compared to traditional piecemeal on-site construction [3, 4]. Since building elements can be selected to achieve automated production in factories and assembled on site through the semimanufacturing construction method, interchangeable terminologies associated with prefabricated construction in the existing literature include off-site prefabrication [5], off-site construction [6], and off-site manufacturing construction [7].

Prefabricated concrete construction can be regarded as a widely accepted alternative to conventional cast-in-situ concrete construction owing to numerous benefits for investors and contractors, such as safer construction environments, faster construction progresses, enhanced quality outputs, and less labour rework on-site [8–10]. Construction schedule can be significantly shortened as a large number of construction activities that can be automated and finished in manufacturing factories. The indoor built environment also contributes to improved construction safety, and construction activities with high health and safety risks can be effectively reduced or even avoided on construction sites [11]. In a factory-controlled environment, there is less risk for problems associated with moisture, environmental hazards, and dirt, and there are strict factory processes and procedures that protect workers from on-the-job injury [12–14]. As for environmental sustainability, prefabricated concrete construction offers benefits in waste reduction [15], facilitates the reuse of some components [16], and reduces water consumption [17]. Prefabricated building modules can also be designed and fabricated with requests of clients to meet living comfort requirements [18].

Based on the aforementioned merits, prefabricated buildings (PRBs) have also been greatly developed to meet the requirements of sustainability and housing demand in China [1]. China has also embarked on several initiatives to promote prefabrication [19]. For instance, the Ministry of Housing and Urban-Rural Development recently stated that China will strive to increase the proportion of PRBs to 30% of new building areas and increase the number of highly skilled industrial workers to 3 million within 10 years [20]. However, in comparison to traditional building (TRB) construction, there are also notable disadvantages that should be considered, such as transportation restrictions and span limits [21]. PRB projects also require increased and more detailed coordination at all stages, which increases the difficulty in progress monitoring and planning. From the economic perspective, prefabricated components incur more initial investment, higher taxes, and more incremental costs [22, 23].

2. Literature Review

Considering availability and selection of the construction techniques, the economic analysis of PRB projects should be conducted for projecting the potential expenditure and indicating their economic benefits. Recently, Jeong et al. [24] selected a case study in South Korea and evaluated several performance indices through the Web-CYCLONE simulation when replacing conventional steel-reinforced concrete columns with form-latticed prefabricated steel-reinforced concrete columns. The results found cost savings of 1.32%. In 2017, Afzal et al. [25] proposed research involving the economic estimation and performance for both prefabricated and conventional construction techniques. Their study reported a sound cost performance of about 5.74 million PKR (Pakistani Rupee) when prefabrication was used for the construction of the given case study building project. However, some studies have expressed concerns regarding the practicability of prefabricated construction in terms of its economical effectiveness [26, 27]. For example, a perceived higher cost has been seen as one of the four main barriers in Australia's prefabricated construction [28]. In particular, material increment costs and labour costs are capable of producing significant impacts on the production cost [29]. In 2018, Hong et al. [1] investigated basic cost composition of prefabrication and examined the effects of adopting prefabrication on the total cost of building projects. Results suggested that transportation could account for 10% of the total cost and the average incremental cost was linearly correlated with the prefabrication rate, which ranged from ¥237/m^2 to ¥437/m^2 for the selected projects. The work of Mao et al. [23] also conducted an analysis on expenditure items of prefabricated and conventional construction methods through a case study approach in China. The research compared the civil project budget costs of a residential building designed in accordance with the PRB design and traditional design schemes based on bid documents and construction drawings, indicating that the PRB incremental cost could reach ¥32/m^2.

Overall, economic benefits of implementing prefabricated construction techniques should be clarified. It is, therefore, necessary to comprehensively evaluate economic benefits from PRB projects in order to break the economic barrier and promote the development of PRBs in China. In particular, the potential economic effects produced by resource-use efficiencies, project progress, and incentive policies need to be further investigated in China's construction industry. Moreover, developing an appropriate pattern for obtaining accurate cost data and reasonable mathematical models for providing a comparative analysis of TRB and PRB projects are also challenges. In addressing these challenges, building information modelling (BIM), as a digital model-based process, emerges as a solution to rapidly simulate and identify the economic impacts of different construction techniques.

Building information modelling (BIM) is regarded as an engineering data platform that integrates various data from engineering projects based on three-dimensional (3D) digital technologies [30]. Refined 3D models can be used to correlate the schedule and cost information of the whole construction process through simulation [31, 32]. The automatic calculation tools of BIM platforms are also capable of effectively reducing error rates for the cost calculation results. In addition, BIM has been applied to prefabricated construction [33]. For example, in 2017, a new BIM-based 4D construction simulation framework was proposed by Lee and Kim [34] to explore the improved management method for modular construction projects. On the basis of the new framework, a visually optimal manufacturing process was identified from the perspectives of resources, material, and quality, and it was also verified that time and cost for module manufacturing could be reduced by the proposed framework. Furthermore, the work of Baltasi and Akbas [35] demonstrated a preconstruction cost analysis method using BIM and prototype resource integrated planning and simulation software, namely, GSimX, proving that the BIM-based cost estimation method was capable of rapidly and accurately producing economic results. The synergy of integrating BIM and prefabrication could also minimise unnecessary and costly rework and conserve resources [36].

Yet, relatively little research exists regarding the comprehensive economic evaluation by adopting BIM within the prefabrication industry, and few mathematical models considering possible economic values are caused by time and political factors. Thus, the research in this paper aims to propose a comparative analysis of TRB and PRB projects based on BIM simulation. PRB projects are rationally transformed into TRB projects through case study method on a BIM platform. The proposed mathematical models consider potential economic effects produced by resource-use efficiencies, project progress, and incentive policies to conduct a comprehensive economic evaluation. The assessment measure can be beneficial for decision makers to consider appropriate construction techniques in building construction projects.

3. Methodology

In order to comprehensively investigate economic benefits of implementing prefabricated construction techniques, this research establishes a framework for evaluating multidimensional economic benefits in terms of three aspects, namely, resource-use efficiencies, project progress, and incentive policies.

First, the corresponding models are proposed after determining the economic composition in terms of resource-savings, shortening of construction periods, and latest policy subsidies. Specifically, construction activities and construction machinery that consume different resources, such as water, electricity, and fuel, are identified in order to explore the potential economic benefits from saved resources. On the basis of this idea, prefabricated construction activities from component production to on-site assembling stages and conventional construction activities are fully demonstrated. Various activities with shorter duration are also sorted to identify the economic benefit indicators related to shortening construction periods. Furthermore, since policy subsidies mainly affect capital performance, all cash inflows and outflows during the whole period, including fund raising, land purchase, construction, and building sales, are identified by the study. Policy subsidies, such as financial subsidies, tax incentives, and sales incentives, are analysed to investigate the composition terms of the economic benefits when the latest policy subsidies are adopted.

Second, the results are produced through the BIM-based simulation, in which the same case study is transformed from PRB into TRB. This is because the comparative analysis using two similar but different cases may result in inaccurate evaluation. In addition, BIM platforms based on commonly used commercial software tools are capable of producing relatively reliable data and calculation results.

3.1. Modelling of Resource-Use Efficiencies. As mentioned previously, the economic benefits of PRB projects from the perspective of the resource-use efficiency are mainly derived from cost savings since prefabricated construction can reduce the use of natural resources and energy, such as water, electricity, coal, petrol, and diesel. Compared with the conventional cast-in-situ construction techniques, the prefabricated construction pattern can achieve automated production in factories and adopt on-site assembly procedures. Thus, labour cost can also be significantly decreased by the mechanisation. Figure 1 demonstrates the composition of economic benefits from saved resources through the identification of differences between the conventional and prefabricated construction techniques.

Economic benefits of resource-savings in prefabricated construction can be formulated as

$$\begin{aligned}\mathrm{IC}_r &= \mathrm{IC}_{r,\mathrm{A1}} + \mathrm{IC}_{r,\mathrm{A2}} + \mathrm{IC}_{r,\mathrm{A3}} \\ &= \left(\mathrm{IC}_{r,\mathrm{A11}} + \mathrm{IC}_{r,\mathrm{A12}} + \mathrm{IC}_{r,\mathrm{A13}}\right) \\ &\quad + \left(\mathrm{IC}_{r,\mathrm{A21}} + \mathrm{IC}_{r,\mathrm{A22}} + \mathrm{IC}_{r,\mathrm{A23}}\right) + \left(\mathrm{IC}_{r,\mathrm{A31}} + \mathrm{IC}_{r,\mathrm{A32}}\right) \\ &= P_{\mathrm{w}}\left[\alpha_1 \cdot Q_1 + \alpha_2 \cdot Q_2 + \alpha_3 \cdot S\right] + P_{\mathrm{e}}\left[\left(\beta_1 \cdot Q_{\mathrm{Ts}} + \beta_2 \cdot \Delta Q_3\right) \right. \\ &\quad \left. + \left(\beta_3 \cdot Q_{\mathrm{Tt}} + \beta_4 \cdot \Delta Q_4\right) + \beta_5 \cdot S\right] \\ &\quad + P_o\left[\left(\gamma_1 \cdot Q_{\mathrm{Tm}} + \gamma_2 \cdot \Delta Q_5\right) + \gamma_3 \cdot S\right],\end{aligned} \tag{1}$$

where IC_r represents the economic benefits of resource-savings; Q_1 and Q_2 (m^3) denote the engineering quantities of beam-column junctions and prefabricated components, respectively; S (m^2) represents the gross floor area; Q_{Ts} (t/machinery one-shift) denotes the power consumed by electrical machines for steel engineering in the simulated TRB projects; ΔQ_3 (t/machinery one-shift) indicates the incremental consumption of machines for steel engineering; Q_{Tt} (m^2/machinery one-shift) represents the consumption of machines for the formwork engineering of wall-column junctions in the simulated TRB projects; ΔQ_4 (m^2/machinery one-shift) denotes the incremental consumption of machines for the formwork engineering of wall-column junctions; Q_{Tm} (m^3/machinery one-shift) denotes the consumption of machines for the scaffolding engineering in the simulated TRB projects; ΔQ_5 (m^3/machinery one-shift) represents the incremental consumption of machines for the scaffolding engineering; P_{w}, P_{e}, and P_{o} represent the unit prices of water, electricity, and diesel; and α, β, and γ are coefficients.

3.2. Modelling of Reduced Construction Time. Reducing construction time without sacrificing quality is beneficial for saving construction project costs, decreasing loan interest payments, and avoiding some finance charges. Thus, shortening construction periods resulting from prefabricated construction can offer several economic benefits. Figure 2 displays the potential economic benefits from the perspectives of capital charges and construction costs, which are used to compare with the conventional cast-in-situ construction technique.

Economic benefits of shorter construction periods caused by adopting prefabricated construction techniques, IC_t, can be defined as

$$\begin{aligned}\mathrm{IC}_t &= \mathrm{IC}_{t,\mathrm{B1}} + \mathrm{IC}_{t,\mathrm{B2}} + \mathrm{IC}_{t,\mathrm{B3}} \\ &= \mathrm{IC}_{t,\mathrm{B1}} + \left(\mathrm{IC}_{t,\mathrm{B21}} + \mathrm{IC}_{t,\mathrm{B22}}\right) + \left(\mathrm{IC}_{t,\mathrm{B31}} + \mathrm{IC}_{t,\mathrm{B32}} + \mathrm{IC}_{t,\mathrm{B33}}\right) \\ &= \sum_{k=1}^{\Delta N} \frac{P_k \cdot \Delta N \cdot i_k}{\left(1 + i_k\right)^{\Delta N}} + \sum_{n=1}^{2} \Delta T1 \cdot P_{ml_n} + \sum_{t=1}^{3} \Delta T2 \times P_{my_t} \\ &\quad + \Delta T3 \times P_{my_c},\end{aligned} \tag{2}$$

where ΔN represents the reduced number of days for the loan payment; i_k and P_k indicate the interest rate and total amount of the loan payment, respectively; $\Delta T1$, $\Delta T2$, and $\Delta T3$ denote the reduced number of days for the construction progress, decoration engineering, and concrete engineering,

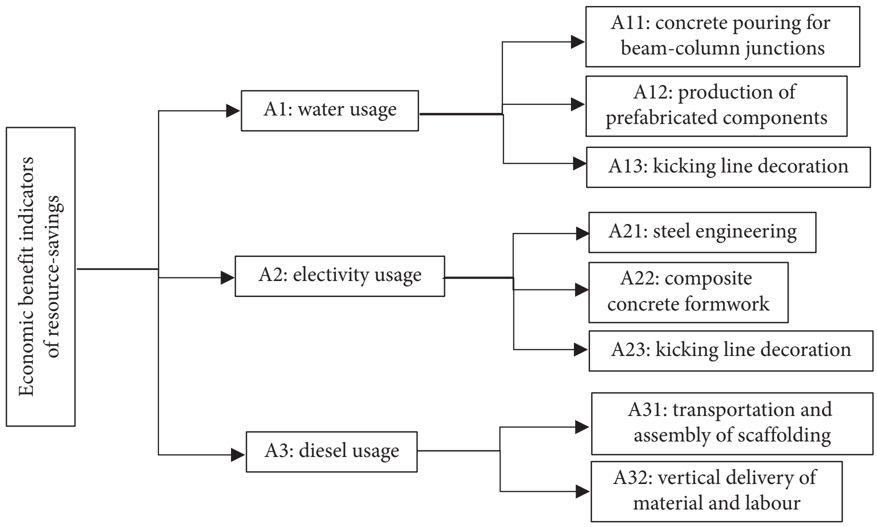


Figure 1: Economic benefits of resource-savings in prefabricated construction.

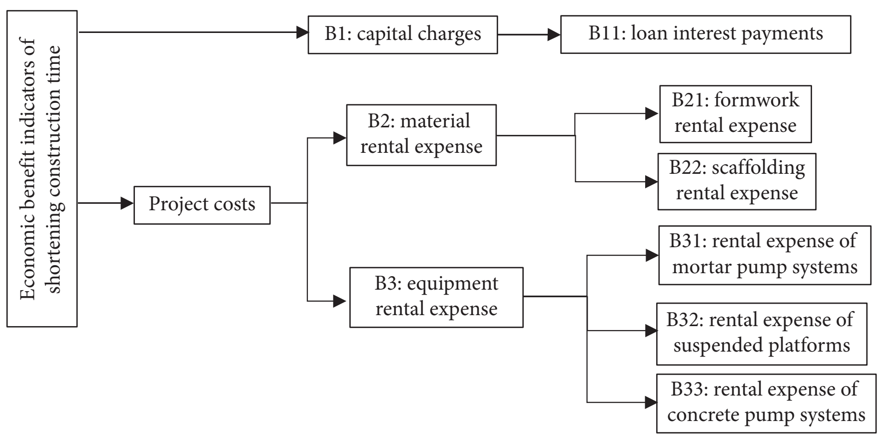


Figure 2: Economic benefits of shortening construction time in prefabricated construction.

respectively; and P_{ml_n}, P_{my_t}, and P_{my_c} represent the unit rental price of the nth item, such as formwork and scaffolding, the unit rental price of the tth type of equipment, such as mortar pump systems and suspended platforms, and the unit rental price of concrete pump systems, respectively, in ¥/month.

3.3. Modelling of Policy Subsidies. At the early stage of development, local governments often issue several incentive policies, such as financial subsidies and tax incentives, for the adoption and spread of prefabricated construction techniques. These incentive policies not only decrease the PRB project costs and reduce loan payments but also bring more economic returns on invested projects. Various economic factors should be considered, such as the subsidies for the unit price per m^2, the proportion for value-added tax exemption, the proportion for enterprise income tax exemption, and the subsidies in terms of floor area ratios (Figure 3).

Economic benefits of policy subsidies caused by adopting prefabricated construction techniques, IC_p, can be expressed as equation (3), where a compound interest algorithm is used to calculate the savings in repayments and taxes:

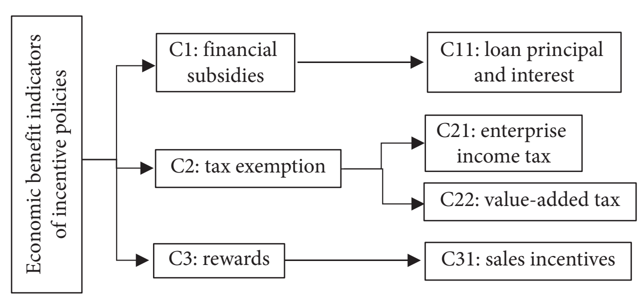


Figure 3: Economic benefits of incentive policies in prefabricated construction.

$$\begin{aligned}\mathrm{IC}_p &= \mathrm{IC}_{p,\mathrm{C1}} + \mathrm{IC}_{p,\mathrm{C2}} + \mathrm{IC}_{p,\mathrm{C3}} \\ &= \mathrm{IC}_{p,\mathrm{C11}} + \left(\mathrm{IC}_{p,\mathrm{C21}} + \mathrm{IC}_{p,\mathrm{C22}}\right) + \mathrm{IC}_{p,\mathrm{C31}} \\ &= \sum_{k=1}^{N} \frac{S \cdot a \cdot (1+i_k)}{(1+i_k)^N} + \left(P_z \cdot J + b \cdot P_q\right) \\ &\quad + c \cdot \left(\frac{S \cdot P_d}{Sl} + S \cdot P_b\right),\end{aligned} \tag{3}$$

where S and Sl represent the floor area and the land area; i_k indicates the interest rate for the kth year; a indicates the subsidies for the unit price per m^2; N denotes the Nth repayment period; J denotes the proportion for value-added tax exemption; P_z and P_q represent the expenditures on value-added tax and enterprise income tax, respectively; P_d and P_b represent the unit prices per m^2 for land and building; b indicates a proportion of enterprise income tax exemption; and c represents a proportion of a sold floor area, based on which local governments reward the sales of prefabricated buildings.

4. Background and Data on the Case Study

4.1. The Selected Case. For the preliminary application of the algorithm proposed in the previous section, an existing apartment building is chosen as a case study to demonstrate the comprehensive economic evaluation, including resource-use efficiencies, project progress, and incentive policies. The selected project is located in Qingpu District, Shanghai, China. The project can be seen as a representative case as it is applicable to incentive policies issued by the local government. The left image of Figure 4 displays the target building, based on which the BIM model is developed using Autodesk Revit by the researcher, as illustrated in the right image. The Revit BIM platform provides rich data and information on building materials and construction techniques [38, 39].

The selected building adopts an assembled integral shear wall structure. The total ground area is 4,015 m^2. The main load-bearing prefabricated components include prefabricated laminated panels, prefabricated stairs, prefabricated balconies, and prefabricated exterior walls. Non-load-bearing prefabricated components are prefabricated interior walls and precast concrete facade panels. Figure 5 displays the transformation between the prefabricated construction technique and the cast-in-situ construction technique on the Revit platform. Prefabricated components provide embedded anchors, which are used for crane lifting. Additionally, prefabricated exterior walls often have thicker protective layers than cast-in-situ exterior walls to avoid subsequent decoration engineering. Steel trusses of prefabricated laminated boards aim to reduce steel fixing tasks.

The total duration of this case project was 207 days, from 10 March 2017 to 3 October 2017, and the duration of the main construction phase and decorating phase was 85 and 59 days, respectively. Figure 6 demonstrates the differences between prefabricated and cast-in-situ construction techniques, which are implemented on the Revit platform to simulate their construction processes. The construction project duration changes with the change in the construction process. The resulting simulation is illustrated in the next section.

4.2. Data Preprocessing. Values of variables and coefficients should be determined after the case is selected. The coefficients of equation (1), namely, α, β, and γ, are identified based on construction codes, such as Consumption Quota of Prefabricated Construction (TY01-01(01)-2016) [41], Consumption Quota of Building Construction and Decoration Engineering (TY01-31-2015) [42], and Unified National Consumption Quota of Machinery and Equipment [43]. Table 1 lists the coefficients by analysing primary construction procedures, such as production of prefabricated components, hoisting, concrete pouring, and decoration, and investigating various fees, such as labour, materials, machines, and measures.

Each coefficient of resources-savings for water, electricity, and diesel equals unit resource consumption of the TRB project minus unit resource consumption of the corresponding PRB project. Thus, only the positive coefficients, which refer to the saving parts of PRBs compared with TRBs, are considered. Water savings come from the different construction activities, and the values of α_1, α_2, and α_3 refer to $\text{Cell}_{2,4}$ of Row 2 and Column 4, $\text{Cell}_{1,4}$, and $\text{Cell}_{17,4}$ in Table 1, respectively. Electricity-related and diesel-related savings are derived from the energy consumption of different types of construction machinery and equipment in construction activities. The values of β_1 and β_2 can be determined by summing Rows 6–11 of Column 5 and summing Rows 6–11 of Column 6, respectively. The values of β_3, β_4, and β_5 refer to the sum of Rows 12–14 in Column 5, the sum of Rows 13–14 in Column 6, and $\text{Cell}_{17,6}$. γ_1 is the sum of $\text{Cell}_{15,7}$ and $\text{Cell}_{15,8}$, and the values of γ_2 and γ_3 come from $\text{Cell}_{15,8}$ and $\text{Cell}_{16,8}$, respectively. Furthermore, in this case study, Q_1, Q_2, ΔQ_3, ΔQ_4, ΔQ_5, and S are defined as 425.64 m^3, 750 m^3, 38.28 t/machinery one-shift, 643500 m^2/machinery one-shift, 2921.63 m^3/machinery one-shift, and 4015 m^2, respectively, according to construction drawings, cost plans, procurement files, and other documents. Q_{Ts}, Q_{Tt}, and Q_{Tm} are 674.87 t/machinery one-shift, 56545.02 m^2/machinery one-shift, and 4549.92 m^3/machinery one-shift, respectively, based on the BIM simulation and Codes for Design of Concrete Structures [44]. The unit prices of water, electricity, and diesel (P_w, P_e, and P_o) are set as 4.57 ¥/t, 1.86 ¥/kwh, and 6.1 ¥/L, respectively.

It is assumed that the financial resources are mainly derived from the available capital and bank loans. Table 2 lists the detailed information on the project investment and plans. The loan for the first phase, ¥1,012,700, is used for the initial investment. The total investment capital is ¥6,000,000. The investment from the available capital must be more than 20% of the total investment capital, according to the rules. Thus, the available capital is ¥2,988,000. The loan capital is ¥3,012,000 in terms of the interest rate of 1.85%.

In addition, according to incentive policies issued by local governments in China [45, 46], the subsidies for the unit price per m^2, a, are set as ¥100/m^2 in equation (3). The proportion for value-added tax exemption, J, is defined as 100%. In addition, there is a proportion of 15% in the enterprise income tax exemption, namely, $b = 0.15$. Local governments reward the sales of prefabricated buildings in terms of 3% of a sold floor area, namely, $c = 0.03$.

5. Results and Analysis of Simulated Economic Benefits

5.1. Specific Performances of Economic Indicators

5.1.1. Resource-Saving Perspective. The BIM platform is used to simulate these two construction processes. Collected data

Figure 4: Target building provided by the construction company [37] and architectural rendering developed by the researchers.

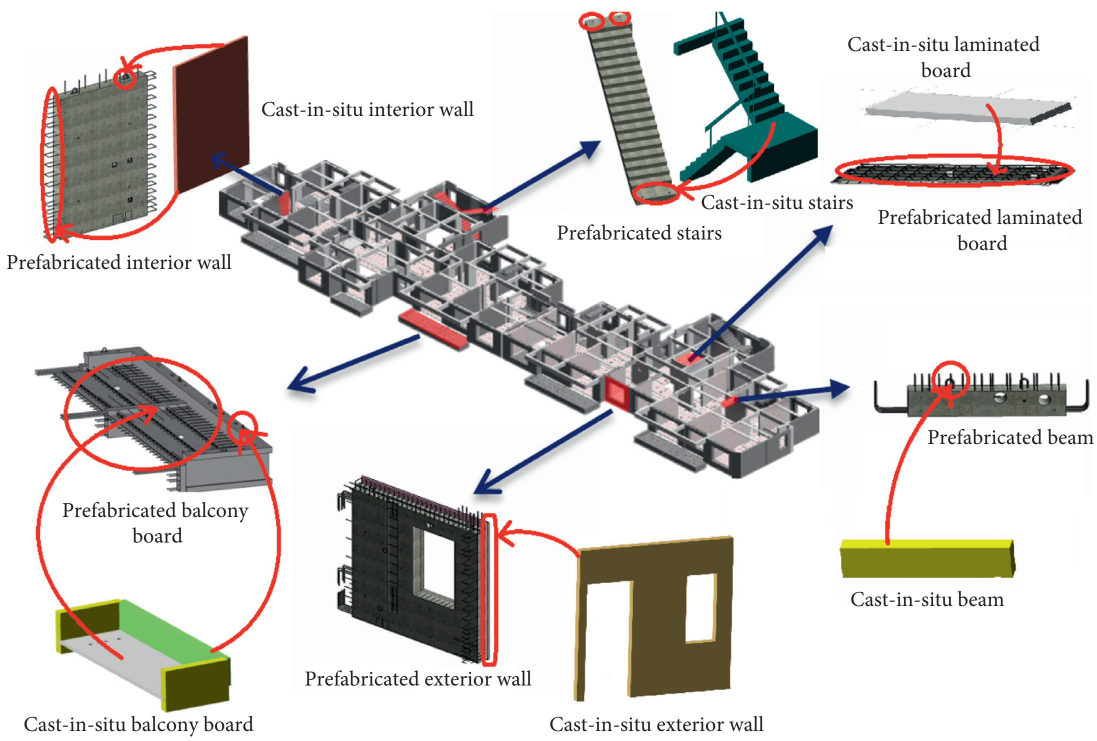


Figure 5: Transformation between prefabricated components and cast-in-situ components, developed by the researchers.

on relevant designs and project consumption quantities are then substituted into equation (1) of the economic evaluation. For prefabricated construction, the increments of economic benefits per m^2 are summarised in Table 3 by comparison.

By summing all values, it can be concluded that the total economic benefit from resource-savings is ¥52.52/m^2. The cost savings in water consumption reaches ¥17.1/m^2 and accounts for 32.6% of the total reduced cost, as illustrated in Figure 7. Unlike concrete, which is manually cured and vibrated, steam curing of concrete is capable of accurately controlling the usage of water and power in manufacturing factories. Furthermore, water-saving mainly occurs in the three construction activities, namely, concrete pouring of column-beam junctions (A11), production of prefabricated components (A12), and kicking line decoration (A13). These indicators can offer corresponding economic benefits of ¥1.005/m^2, ¥0.92/m^2, and ¥15.2/m^2, respectively. Indicator A11 accounts for the proportion of 5.9%, A12 for 5.4%, and A13 for 89.6% from the water-saving perspective. Furthermore, prefabricated construction produces a saved cost of ¥4.3/m^2 owing to the electricity-use efficiency, which accounts for 8.2% of the total reduced cost. Economic merits of ¥2.1/m^2, ¥2.0/m^2, and ¥0.23/m^2 occur in construction activities of steel engineering (A21), composite concrete formwork (A22), and kicking line decoration (A23). In addition, prefabricated construction can save a cost of ¥31.1/m^2 due to the higher utilisation rate of diesel oil. PRB projects often require less fuel-consumption machinery and equipment, such as concrete pump trucks. The economic

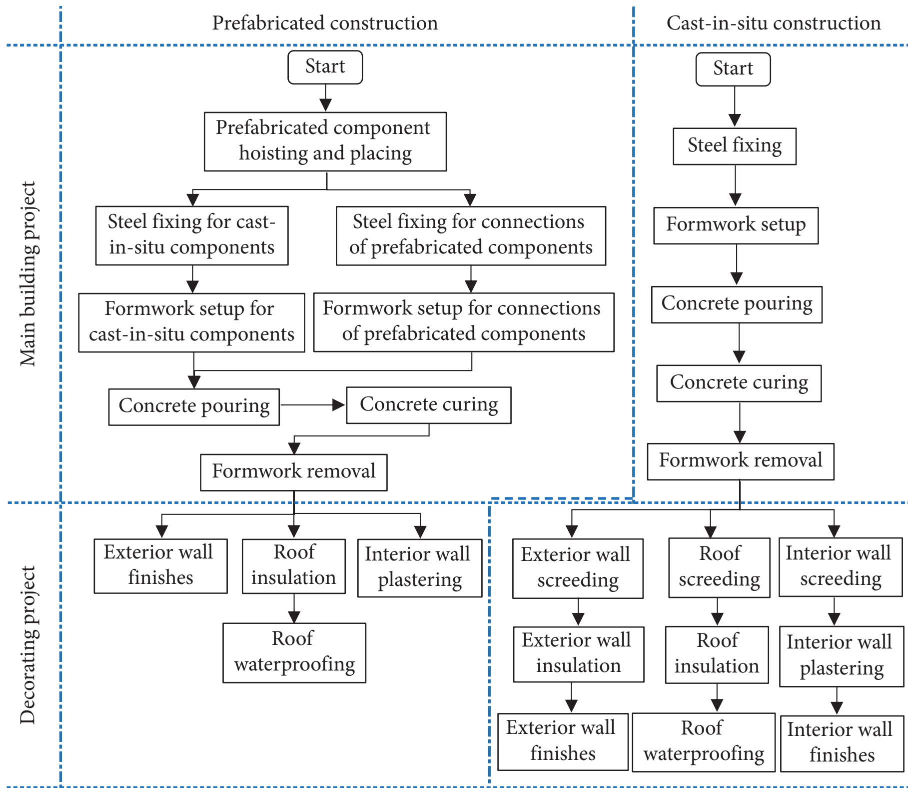


Figure 6: Simulated prefabricated and cast-in-situ construction processes developed by the researchers, referring to the construction code [40].

value accounts for 59.2% of the total reduced cost, consisting of saved costs of ¥25.1/m^2 in the scaffolding engineering (A31) and ¥5.05/m^2 in the vertical delivery (A32). Overall, the saved consumption of diesel oil can be considered the most significant contributor from the resource-saving perspective.

5.1.2. Time-Saving Perspective. The number of days for loan repayments, the total repayment, and the construction time are derived from construction management plans and financial reports. Based on the Construction Period Quota of Building Installation Engineering (TY01-89-2016), the repayment days and the construction duration are calculated. These two periods are reduced by 20 and 35 days, respectively. Reducing repayment time is beneficial to save expenses on loan interest payments. Reducing construction time results in the decrease in material rental expenses, such as formwork and scaffolding, and equipment rental expenses, such as pumps and platforms. Table 4 lists the results of economic merits by shortening the construction period.

The total economic benefit by shortening the construction period reaches ¥552.9/m^2, in which the reduced expense on the loan interest payment (B1) is ¥173.3/m^2 and accounts for 31.3% of the total reduced expenses. The benefit from the saved expenses reaches ¥379.64/m^2, consisting of the material rental (B2) and equipment rental (B3). Indicators B2 and B3 produce the economic merits of ¥170.2/m^2 (30.8%) and ¥209.5/m^2 (37.9%,), respectively, as shown in Figure 8, but there is little difference between their proportions. The B2-related economic value is mainly derived from the saved expenses on the formwork rental (B21) and the scaffolding rental (B22). B21 and B22 account for 46.2% and 53.9% of B2, respectively. In addition, adopting prefabricated construction can save expenses of ¥43.1/m^2 in the rental of mortar pump systems (B31), ¥28.9/m^2 in the rental of suspended platforms (B32), and ¥137.5/m^2 in the rental of concrete pump systems (B33). B31, B32, and B33 account for 20.6%, 13.8%, and 65.6% of B3, respectively.

5.1.3. Policy Perspective. Table 5 provides the results of economic merits due to the transformation from the prefabricated construction technique to the conventional cast-in-situ.

Specifically, the total economic benefit by adopting the latest incentive policies reaches ¥155.63/m^2. The reduced expense on the principal and interest (C11) is ¥8.9/m^2 because of financial subsidies (C1). It accounts for 5.7% of the total economic benefit, as shown in Figure 9. In addition, it should be noted that the tax exemption (C2) is only available to prefabricated building projects, which are checked and identified by local governments in terms of building area, assembly rate, structural characteristic, and construction technology in China. Other sustainable construction projects, such as green buildings, are only stimulated by means of financial subsidies. As for the selected case, the benefit from the tax exemption (C2) reaches ¥66.4/m^2, consisting of the enterprise income tax exemption (C21) and value-added

Table 1: Resource-use-related coefficients.

Sequence number	1	2	3	4	5	6	7	8
	Construction activities	Use of machinery and equipment		Resource-savings				
		Machines	Differential	Water (m^3) (TRB-PRB)	Electricity (kW) (TRB)	Electricity (kW) (TRB-PRB)	Diesel (kg) (TRB)	Diesel (kg) (TRB-PRB)
1	Production, concrete pouring, and concrete curing of prefabricated components			1.03				
2	Concrete pouring, vibration, and curing of column-beam junctions			0.015	0.372	−0.444		
3	Concrete pouring, vibration, and curing of superimposed beam-slab junctions			−0.16	0.372	−0.06		
4	Concrete pouring, vibration, and curing of superimposed shear wall junctions			−0.01	0.372	−0.2862		
5	Concrete pouring, vibration, and curing of wall-column junctions			−1.13	0.372	−0.2808		
6	Processing, delivery, fixing, and installation of steel bars	Steel bar straightening machines 40 mm/machinery one-shift/t	0	0	0.952	0		
7		Steel bar cutting machines 40 mm/machinery one-shift/t	0.01		2.889	0.321		
8		Steel bar bending machines 40 mm/machinery one-shift/t	0.03	0	7.383	0.963		
9		DC welding machines 32 KVA/machinery one-shift/t	0.01	0	33.06	0.936		
10		Butt-welding machines 75 KVA/machinery one-shift/t	0.01	0	11.061	1.229		
11		Welding electrode drying ovens $45 \times 35 \times 45$ (cm^3)/machinery one-shift/t	0.001	0	0.2546	0.0067		
12	Formwork setup of column-beam junctions	Woodworking circular sawing machines 500 mm/machinery one-shift/100 m^2	−0.019	0	0.00132	-0.456		
13	Formwork setup of wall-column junctions	Woodworking circular sawing machines 500 mm/machinery one-shift/100 m^2	0.015	0	0.00132	0.0036		
14	Splices of composite wood boards	Woodworking circular sawing machines 500 mm/machinery one-shift/100 m^2	0.011	0	0.00132	0.00264		
15	Scaffold delivery, assembly, and removal	Heavy trucks 6 t/machinery one-shift/m^2	0.0735	0		0	0.61	2.37
16	Vertical delivery	Tower cranes 1000 kNm/machinery one-shift/100 m^2	0.00172	0		0	5.75	0.53
17	Kicking line decoration	100 m^2	0	3.41	0.126	0.126		

Table 2: Project financing and investment plans.

Item	Capital (¥1000)	Project progress (¥1000) Phase 1	Phase 2	Phase 3	Phase 4
Construction investments	5,891.4	1,777.4	1,692.9	1,514.4	906.4
Loan interest	108.9	32.9	31.3	28.0	
Total investment	6,000	1,810.2	1,724.3	1,542.4	906.4
Available capital	2,988	1,896	660	432	
Loan	3,012	1,012.7	1,056	943.3	
Project financing	6,000	2,908.7	1,716	1,375.3	

Table 3: Results of economic merits brought by resource-savings (¥/m^2).

	Water	Power	Diesel	Sum	Total
Concrete pouring of column-beam junctions (A11)	1.005	—	—	17.1	52.5
Production of prefabricated components (A12)	0.92	—	—		
Kicking line decoration (A13)	15.2	—	—		
Steel engineering (A21)	—	2.1	—	4.3	
Formwork engineering of column-beam junctions (A22)	—	2.0	—		
Kicking line decoration (A23)	—	0.2	—		
Scaffolding engineering (A31)	—	—	25.1	31.1	
Vertical delivery engineering (A32)	—	—	5.05		

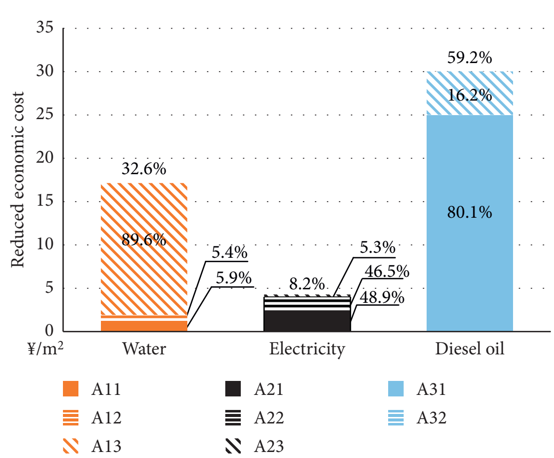


Figure 7: Economic proportions of indicators from resource-saving perspective.

tax exemption (C22). These two factors, C21 and C22, offer the economic merits of ¥23.9/m^2 and ¥42.4/m^2, respectively, accounting for 36% and 64% in C2. The local government rewards investors in terms of sold floor areas of PRB projects. Thus, the sales incentives (C31) increase by ¥80.4/m^2,

Table 4: Results of economic merits by shortening construction period (¥/m^2).

Item		Cost-saving	Sum	Total
Capital charges (B1)	Loan interest payments (B11)	173.3	173.3	552.9
Material rental expense (B2)	Formwork (B21)	78.5	170.2	
	Scaffolding (B22)	91.7		
Equipment rental expense (B3)	Mortar pump systems (B31)	43.1	209.5	
	Suspended platforms (B32)	28.9		
	Concrete pump systems (B33)	137.5		

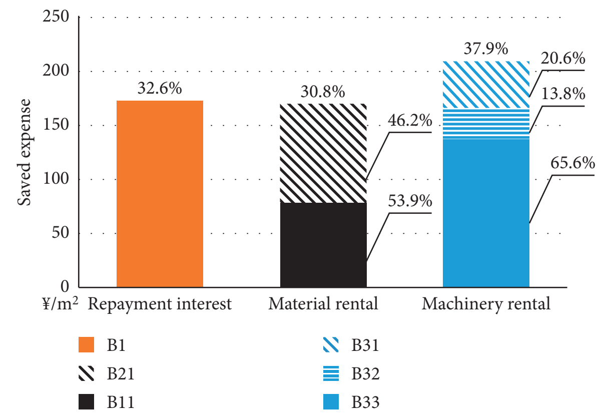


Figure 8: Economic proportions of indicators from time-saving perspective.

Table 5: Results of economic merits by adopting incentive policies (¥/m^2).

Item		Obtained benefits	Sum	Total
Financial subsidies (C1)	Loan principal and interest (C11)	8.9	8.9	155.63
Tax exemption (C2)	Enterprise income tax (C21)	23.9	66.4	
	Value-added tax (C22)	42.4		
Rewards (C3)	Sales incentives (C31)	80.4	80.4	

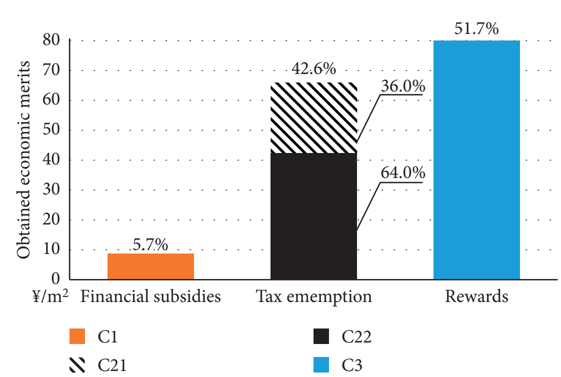


Figure 9: Economic proportions of indicators from policy perspective.

which accounts for 51.7% of the total economic benefit by adopting the latest incentive policies of prefabricated construction.

5.2. Overall Performances of Economic Benefits. Previous research suggested that the increased cost can reach between ¥464.41/m^2 and ¥783.94/m^2 when adopting prefabricated construction in China [47, 48]. However, the present research considers that the comprehensive economic merit can reach ¥739.6/m^2 through higher resource-use efficiencies, faster project progress, and current incentive policies for the adoption of prefabricated construction. The proposed economic benefit is capable of offsetting the incremental cost and even producing revenues. In addition, the comprehensive incremental benefit and its economic components are not directly affected by the size of the site. As discussed in Section 3, the benefit evaluation of saving resources mainly relies on materials and other resources consumed by machines. The benefit evaluation of shortening construction time is determined by the project progress, and the benefit evaluation of receiving policy subsides is related to building size and application situation of prefabricated construction technologies. However, comprehensive economic benefit of a PRB project is often positively correlated with its scale. Increasing the project scale is capable of promoting the economic benefit. For example, from the resource-saving perspective, a larger floor area means that more building components are fabricated and more construction materials, such as formwork, are reused in manufacturing factories. A larger floor area also means that more building components, such as exterior walls, are prefabricated, and thus, the on-site construction progress can be more significantly accelerated. Equation (3) also indicates that the subsidies and rewords are related to the project scale. In this case, the economic benefit from shortening the construction period can be regarded as the most significant contributor, namely, ¥552.9/m^2, accounting for 74.8% of the comprehensive economic evaluation. The current incentive policies contribute the smallest value of the comprehensive economic evaluation, namely, ¥52.3/m^2, which accounts for 7.1%.

In order to further identify the temporal change of the comprehensive economic benefit in the project, the economic benefits of saving resources, shortening construction time, and receiving policy subsides with the construction period are calculated for main construction days in terms of equations (1)–(3). The results are listed in Table 6 and plotted in Figure 10 to display the temporal changes in economic benefits over a project period.

The building project progress can be divided into three phases, namely, construction phase, decoration phase, and sales phase. After the construction and decoration phases, there are no economic benefits caused by resource- or time-savings. Yet, the comprehensive economic merit will be increased to ¥739.6/m^2 owing to sales incentives. For this building project, the duration of the construction phase is from Day 1 to Day 85 and the decoration phase is from Day 85 to Day 207. Figure 10 demonstrates that the comprehensive incremental benefit has significant growth between Day 1 and Day 110.

Table 6: Economic benefit values on main days in the project.

Construction period (day)	Economic benefits (¥/m^2)			
	Resource-saving	Time-saving	Policy subsidies	Comprehensive economic benefits
1	2.03	21.37	50.50	73.90
10	4.06	42.74	52.60	99.40
20	6.09	64.11	56.90	127.10
29	12.12	85.48	62.30	159.90
39	15.15	106.85	63.10	185.10
52	17.18	128.22	64.20	209.60
61	22.21	149.59	65.20	237.00
71	25.24	170.96	66.40	262.60
74	29.27	192.33	66.70	288.30
79	34.30	213.70	67.80	315.80
85	38.33	235.07	69.40	342.80
92	41.36	256.44	70.90	368.70
103	42.69	297.81	71.00	411.50
115	43.42	332.18	72.40	448.00
124	44.75	343.55	73.10	461.40
135	45.48	361.92	74.60	482.00
143	46.51	392.29	75.30	514.10
157	47.54	425.66	76.10	549.30
164	48.57	463.03	77.20	588.80
179	49.60	497.40	78.10	625.10
189	51.62	521.77	79.20	652.60
207	52.65	552.95	80.10	685.71
237	52.65	552.95	89.00	694.61
266	52.65	552.95	95.00	700.61
267	52.52	552.95	133.00	738.48

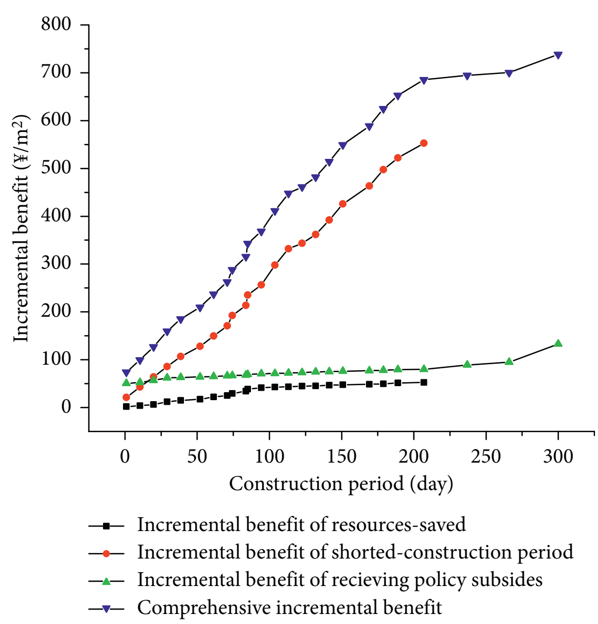


Figure 10: Changes in economic benefits over a project period.

The trend line in the incremental benefit of shorting construction time aims to plot the cumulative economic merits on main days brought by the prefabricated construction technique from the time-saving perspective. It can be observed that there is a rapid increase in the economic merit due to the faster on-site construction progress when selecting the prefabricated construction technique. Its trend change is similar with the line of the comprehensive incremental benefit, and its economic values are greater than other economic components after around Day 20. This means that the time-saving factor can be considered the largest contributor to the economic benefit of the prefabricated construction technique, expect for the early stage of the building project. The fastest growth occurs between Day 90 and Day 207, which means that decoration engineering is more important to incremental values produced by the faster construction progress of the prefabricated construction technique. This is because production of prefabricated components simplifies the on-site work of exterior walls, slabs, and other building parts. High-quality prefabricated components with insulation layers can avoid a number of decoration tasks involving plastering and insulation and reduce the rental expenses on material and equipment.

Furthermore, saving resources has been the lowest contributor to the comprehensive economic benefit over the project period. It experiences a relatively fast growth between Day 25 and Day 85 and a slow increase from Day 85 to Day 207. Compared to the decoration phase, the construction phase can offer more economic benefits due to resource-use efficiencies of prefabricated construction. As for the incremental benefit brought by policy subsidies of prefabricated construction, its relatively fast growth occurs during the early stage of building construction; yet, sales incentives will contribute to the growth of economic benefit caused by policy subsidies after the decoration phase.

6. Conclusions

Overall, prefabricated construction has been considered a widely accepted alternative to conventional cast-in-situ concrete construction since it is capable of offering numerous benefits for investors and contractors. However, researchers hold various viewpoints on economic merits of PRB projects. Thus, considering availability and selection of the construction techniques, the economic analysis of PRB projects, should be conducted for projecting the potential expenditure and indicating their economic benefits. This research aims to comprehensively evaluate the economic benefits of implementing prefabricated construction techniques in order to surpass the economic barrier and promote the development of PRBs in China. The comprehensive economic evaluation is formulated in terms of resource-use efficiencies, project progress, and incentive policies. An apartment building in Shanghai is selected as a case study. Construction progress is simulated on the BIM platform when the same case study is rationally transformed from the prefabricated to the conventional cast-in-situ construction technique. For the adoption of prefabricated construction, the significant economic benefit results from saved resources, shortened construction periods, and policy subsidies.

The results reveal that the comprehensive economic merit can reach ¥739.6/m^2 when selecting the prefabricated construction process. The economic benefit offered by shortening the construction period can be regarded as the most significant contributor because of a large proportion. Among the project-progress-related factors, the reduced expenses on machinery rental and material rental are seen as the largest and smallest parts, respectively, but there is not a significant difference. The reward policy plays the most important role from the policy perspective. It can offer an economic benefit of 80.4/m^2 and account for more than half of the total policy-related economic benefit.

Additionally, the assessment measure can be beneficial for decision makers to consider prefabricated construction techniques in building construction projects in terms of the potential economic benefits. The results can contribute to judicious construction patterns and the efficient utilisation of incentive policies. This research is expected to contribute to further improvement by incorporating more detailed data on construction processes and addressing more economic indicators in future research.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are thankful for the support from the National Key R&D Program of China (2016YFC0701810 in 2016YFC0701800), North China University of Technology Science and Technology Innovation Project (18XN149), and North China University of Technology Yu Jie Talent Development Program (18XN154).

References

[1] J. Hong, G. Q. Shen, Z. Li, B. Zhang, and W. Zhang, "Barriers to promoting prefabricated construction in China: a cost-benefit analysis," *Journal of Cleaner Production*, vol. 172, pp. 649–660, 2018.

[2] D. Yeoh and M. Fragiacomo, "The design of a semi-prefabricated LVL-concrete composite floor," *Advances in Civil Engineering*, vol. 2012, Article ID 626592, 19 pages, 2012.

[3] R. E. Smit, *Off-Site Construction Implementation Resource: Off-Site and Modular Construction Explained*, Off-Site Construction Council, National Institute of Building Sciences, 2014, http://www.wbdg.org/resources/site-and-modular-construction-explained.

[4] R. Y. Zhong, Y. Peng, F. Xue et al., "Prefabricated construction enabled by the Internet-of-Things," *Automation in Construction*, vol. 76, pp. 59–70, 2017.

[5] S. Mostafa, N. Chileshe, and T. Abdelhamid, "Lean and agile integration within offsite construction using discrete event simulation," *Construction Innovation*, vol. 16, no. 4, pp. 483–525, 2016.

[6] M. Arashpour, Y. Bai, G. Aranda-mena, A. Bab-Hadiashar, R. Hosseini, and P. Kalutara, "Optimizing decisions in advanced manufacturing of prefabricated products: theorizing supply chain configurations in off-site construction," *Automation in Construction*, vol. 84, pp. 146–153, 2017.

[7] S. J. Kolo, F. P. Rahimian, and J. S. Goulding, "Offsite manufacturing construction: a big opportunity for housing delivery in Nigeria," *Procedia Engineering*, vol. 85, pp. 319–327, 2014.

[8] V. W. Y. Tam, I. W. H. Fung, M. C. P. Sing, and S. O. Ogunlana, "Best practice of prefabrication implementation in the Hong Kong public and private sectors," *Journal of Cleaner Production*, vol. 109, pp. 216–231, 2015.

[9] Z. Li, G. Q. Shen, and X. Xue, "Critical review of the research on the management of prefabricated construction," *Habitat International*, vol. 43, pp. 240–249, 2014.

[10] N. Blismas, C. Pasquire, and A. Gibb, "Benefit evaluation for off-site production in construction," *Construction Management and Economics*, vol. 24, no. 2, pp. 121–130, 2006.

[11] M. M. Fard, S. A. Terouhid, C. J. Kibert, and H. Hakim, "Safety concerns related to modular/prefabricated building construction," *International Journal of Injury Control and Safety Promotion*, vol. 24, no. 1, pp. 10–23, 2017.

[12] E. M. Generalova, V. P. Generalov, and A. A. Kuznetsova, "Modular buildings in modern construction," *Procedia Engineering*, vol. 153, pp. 167–172, 2016.

[13] E. D. L. Franks, *Safety and Health in Prefabricated Construction: A New Framework for Analysis*, University of Washington, Seattle, WA, USA, 2018.

[14] B.-G. Hwang, M. Shan, and K.-Y. Looi, "Knowledge-based decision support system for prefabricated prefinished volumetric construction," *Automation in Construction*, vol. 94, pp. 168–178, 2018.

[15] D. Matic, J. R. Calzada, M. S. Todorovic, M. Erić, and M. Babin, "Chapter 16-cost-effective energy refurbishment of prefabricated buildings in Serbia," in *Cost-Effective Energy Efficient Building Retrofitting*, F. Pacheco-Torgal, C.-G. Granqvist, B. P. Jelle, G. P. Vanoli, N. Bianco, and J. Kurnitski, Eds., pp. 455–487, Woodhead Publishing, Cambridge, UK, 2017.

[16] R. Minunno, T. O'Grady, G. Morrison, R. Gruner, and M. Colling, "Strategies for applying the circular economy to prefabricated buildings," *Buildings*, vol. 8, no. 9, p. 125, 2018.

[17] O. Pons, "18-assessing the sustainability of prefabricated buildings," in *Eco-Efficient Construction and Building Materials*, F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha, and A. de Magalhães, Eds., pp. 434–456, Woodhead Publishing, Cambridge, UK, 2014.

[18] N. Vieira, M. Amado, and F. Pinho, "Prefabricated solution to modular construction in Cape Verde," *AIP Conference Proceedings*, vol. 184, no. 1, article 020071, 2017.

[19] Y. Chang, X. Li, E. Masanet, L. Zhang, Z. Huang, and R. Ries, "Unlocking the green opportunity for prefabricated buildings and construction in China," *Resources, Conservation and Recycling*, vol. 139, pp. 259–261, 2018.

[20] The state council, "Guiding opinions of the general office of the State Council on vigorously developing prefabricated buildings," 2016, http://www.gov.cn/zhengce/content/2016-09/30/content_5114118.htm.

[21] A. E. Fenner, M. Razkenari, H. Hakim, and C. J. Kibert, "A review of prefabrication benefits for sustainable and resilient coastal areas," in *Proceedings of the 6th International Network of Tropical Architecture Conference, Tropical Storms as a Setting for Adaptive Development and Architecture*, University of Florida, Gainesville, FL, USA, December 2017.

[22] L. Jaillon and C. S. Poon, "Life cycle design and prefabrication in buildings: a review and case studies in Hong Kong," *Automation in Construction*, vol. 39, pp. 195–202, 2014.

[23] C. Mao, F. Xie, L. Hou, P. Wu, J. Wang, and X. Wang, "Cost analysis for sustainable off-site construction based on a multiple-case study in China," *Habitat International*, vol. 57, pp. 215–222, 2016.

[24] J. Jeong, T. Hong, C. Ji et al., "An integrated evaluation of productivity, cost and CO 2 emission between prefabricated and conventional columns," *Journal of Cleaner Production*, vol. 142, pp. 2393–2406, 2017.

[25] M. Afzal, S. Maqsood, and S. Yousaf, "Performance evaluation of cost saving towards sustainability in traditional construction using prefabrication technique," *International Journal of Research in Engineering and Science*, vol. 5, no. 5, pp. 73–79, 2017.

[26] S. Jang and G. Lee, "Process, productivity, and economic analyses of BIM-based multi-trade prefabrication-A case study," *Automation in Construction*, vol. 89, pp. 86–98, 2018.

[27] E. I. Antillón, M. R. Morris, and W. Gregor, "A value-based cost-benefit analysis of prefabrication processes in the healthcare sector: a case study," in *Proceedings of the 22nd International Group for Lean Construction Conference*, Oslo, Norway, June 2014.

[28] N. Blismas and R. Wakefield, "Drivers, constraints and the future of offsite manufacture in Australia," *Construction Innovation*, vol. 9, no. 1, pp. 72–83, 2009.

[29] H. Xue, S. Zhang, Y. Su, and Z. Wu, "Capital cost optimization for prefabrication: a factor analysis evaluation model," *Sustainability*, vol. 10, no. 1, p. 159, 2018.

[30] C. Z. Li, F. Xue, X. Li, J. Hong, and G. Q. Shen, "An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction," *Automation in Construction*, vol. 89, pp. 146–161, 2018.

[31] M. O. Fadeyi, "The role of building information modeling (BIM) in delivering the sustainable building value," *International Journal of Sustainable Built Environment*, vol. 6, no. 2, pp. 711–722, 2017.

[32] S. Song, J. Yang, and N. Kim, "Development of a BIM-based structural framework optimization and simulation system for building construction," *Computers in Industry*, vol. 63, no. 9, pp. 895–912, 2012.

[33] J. Zhang, Y. Long, S. Lv, and Y. Xiang, "BIM-enabled modular and industrialized construction in China," *Procedia Engineering*, vol. 145, pp. 1456–1461, 2016.

[34] J. Lee and J. Kim, "BIM-based 4D simulation to improve module manufacturing productivity for sustainable building projects," *Sustainability*, vol. 9, no. 3, p. 426, 2017.

[35] G. S. Baltasi and R. Akbas, "Structured evaluation of preconstruction cost alternatives with bim and resource integrated simulation," in *Proceedings of the Lean and Computing in Construction Congress-Joint Conference on Computing in Construction*, pp. 499–506, Heraklion, Greece, July 2017.

[36] S. Mostafa, K. P. Kim, V. W. Y. Tam, and P. Rahnamayiezekavat, "Exploring the status, benefits, barriers and opportunities of using BIM for advancing prefabrication practice," *International Journal of Construction Management*, pp. 1–11, 2018.

[37] Longxin Group, 2019, http://www.lxgroup.cn/.

[38] Autodesk, "Revit built for building information modeling," 2019, https://www.autodesk.com/products/revit/overview.

[39] M. Hu, "BIM-enabled pedagogy approach: using BIM as an instructional tool in technology courses," *Journal of Professional Issues in Engineering Education and Practice*, vol. 145, no. 1, article 05018017, 2019.

[40] The Ministry of Housing and Urban-Rural Development, *Code for Construction of Concrete Structures (GB 50666-2011)*, China Architecture & Building Press, Beijing, China, 2012.

[41] The Ministry of Housing and Urban-Rural Development, *Consumption Quota of Prefabricated Construction (TY01-01(01)-2016)*, China Planning Press, Beijing, China, 2017.
[42] The Ministry of Housing and Urban-Rural Development, *Consumption Quota of Building Construction and Decoration Engineering (TY01-31-2015)*, China Planning Press, Beijing, China, 2015.
[43] Housing and Urban-Rural Development Institute of Standards and Norms, *Unified National Consumption Quota of Machinery and Equipment*, China Planning Press, Beijing, China, 2012.
[44] The Ministry of Housing and Urban-Rural Development, *Code for Design of Concrete Structures (GB 50010-2010)*, China Architecture & Building Press, Beijing, China, 2015.
[45] Shanghai Municipal Development and Reform Commission, *Demonstration Projects of Special Support Measures on Building Energy Efficiency and Green Buildings*, Shanghai Municipal Development and Reform Commission, Shanghai, China, 2016.
[46] The General Office of the Municipal People's Government of Beijing, *Implementation Opinions on Accelerating the Development of Prefabricated Buildings*, The General Office of the Municipal People's Government of Beijing, Beijing, China, 2017.
[47] M. Ningning and C. Bingqing, "Analysis on the cost control of prefabricated concrete buildings," *Journal of Fujian University of Technology*, vol. 15, no. 4, pp. 399–403, 2017.
[48] L. Lihong, G. Bohui, Q. Baoku, L. Yunxia, and L. Lan, "Empirical analysis on the cost of prefabricated construction contrast with cast-in-place building," *Construction Economy*, vol. 9, pp. 102–105, 2013.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 1515808, 15 pages
https://doi.org/10.1155/2019/1515808

Research Article

Excavation Safety Modeling Approach Using BIM and VPL

Numan Khan,[1] Ahmad K. Ali,[1] Miroslaw J. Skibniewski,[2,3,4] Do Yeop Lee,[1] and Chansik Park[1]

[1]*School of Architecture and Building Sciences, Chung-Ang University, Seoul 06974, Republic of Korea*
[2]*Professor, Dept. of Civil & Environmental Engineering, University of Maryland, College Park, MD, USA*
[3]*Professor and Member of Research Board, Institute for Theoretical and Applied Informatics, Polish Academy of Sciences, Gliwice, Poland*
[4]*T.-S. Yang Honorary Distinguished Professor, Chaoyang University of Technology, Taichung, Taiwan*

Correspondence should be addressed to Chansik Park; cpark@cau.ac.kr

Received 24 January 2019; Accepted 7 March 2019; Published 10 April 2019

Guest Editor: Tatjana Vilutiene

Soil excavation is a fundamental step of building and infrastructure development. Despite strong enforcement of construction best practices and regulations, accidents in construction industry are comparatively higher than other industries. Likewise, significant increase in injuries and fatalities are recently reported on geotechnical activities such as excavation pits and trenches. Academic researchers and industry professionals have currently devoted vital attention to acquire construction safety in preconstruction phase of the project. They have developed various algorithms to enhance safety in preconstruction phase such as automated generation of scaffolding and its potential risk analysis, checking BIM model for fall risks, and limited access zone allocation in wall masonry. However, safety in geotechnical works at preconstruction phase is yet unexplored. This paper proposed automatic safety rule compliance approach for excavation works leveraging algorithmic modeling tools and BIM technologies. The focused approach comprises of the following three modules: information extraction and logic design (IELD), information conversion and process integration (ICPI), and automodeling and safety plan generation (ASPG). Specifically, the scope of the paper is limited to major risks such as cave-ins, fall, safety egress, and prohibited zones risks. A set of rules-based algorithms was developed in commercially available software using visual programming language (VPL) that automatically generates geometric conditions in BIM and visualizes the potential risks and safety resources installation along with their quantity take-off and optimized locations. A case study has been presented to validate the proof of concept; automated modeling tool for excavation safety planning generated the required results successfully. It is anticipated that the proposed approach has potential to help the designers through automated modeling and assist decision makers in developing productive and practical safety plans compared to the conventional 2D plans for excavation works at the preconstruction phase. Moreover, it is realized that the same approach can be extended to other rule-dependent subjects in construction.

1. Introduction

Safety in construction is a major concern worldwide [1]. Recent studies reported a significant increase in excavation-related accidents [2] and could have been avoided with additional considerations. Soil excavation is an essential step of infrastructure development that includes removing of earth for the foundation installation, cut and fills to create usable lands, and landfill to construct embankments for flood mitigation [3]. In building construction, significance of the excavation works is eminent due to the ultimate base of entire construction. In general, construction projects such as building foundation, utility lines, tunneling, and underpasses require excavation in different makeup, e.g., open excavation, potholing, trenches, and shaft drives. According to safety and health agency in the United States, Occupational Safety and Health Administration, hereinafter referred to as OSHA, excavation typically refers to any man made cut, trench, cavity, or depression made by removal of earth [4]. Despite constant determination from safety professionals, researchers, and imposed safety regulations, injuries and fatalities in construction have not significantly dropped [5]. Unfortunately, geotechnical-related injuries and fatalities are incessantly growing [6]. Digging operations are one of the most challenging among other activities [7, 8], incorporating cave-ins, fall into the pit, working with machinery, deficiency of oxygen, flooding, and many more [6–10]. The unpleasant statistics from the United States (US) revealed the death of more than 30 workers per year in digging operation [11], cave-ins as a severe risk to the worker's life [12]. Likewise, in the private construction industry of US, statistics from 2003 to 2011 show the death of 287 workers caused by trench collapses [13]. These high numbers of accidents make serious contribution to time delays and cost overruns [14]. Earth excavation with a steep vertical or near vertical diggings needs to be protected by sloping, benching, shoring [4, 6, 12], and bracing system to avoid cave-ins or damage to the surroundings [8]. Evidence recorded by OSHA revealed more trench-related accidents in 2016 with the comparison of previous two years (2014 and 2015) combined [2]. Accordingly, OSHA considered pits and trenching hazards as a priority for 2018 [15], with the target of reducing accident rates by ten percent till SEP, 2019 [7]. The facts and indication presented to acknowledge the solemnity of the excavation safety and demand additional focus for proactive safety prevention methods.

In 1970, Occupational Safety Health Act laid the foundation for development of various strategies and safety standards in order to prevent accidents which show significant amelioration in construction safety management [16]. Construction safety performance has been significantly improved over the last four decades due to strong enforcement of these standards and strategies [17]. If these safety standards had not been provided and enforced, then the abovementioned statistics would have been higher than the current numbers [6]. The foundation of construction risks identification is safety standards and regulations [18]; enforcement of these regulations reported [17] in planning and monitoring could minimize the accidents in excavation-related tasks. Analysis of risks is crucial in planning phase to avoid misshapes in the execution and construction phase. Safety in construction was considered sole obligation of the constructor during execution phase of the project [19, 20]. Meanwhile, there is viable understanding about the mitigation of these risks that arise during construction, operation, maintenance, or repair works through proper consideration during design phase [1]. In the UK, establishment of Construction Design and Management (CDM) rules imposed health and safety considerations in the planning and design phase as an obligation [20]. Recently, different software tools are also developed rapidly for implementation of construction safety knowledge in the design phase, for example, "ToolBox" by Construction Industry Institute (CII) for identification of project-specific hazards along with improved design suggestions [21], web-based system by Dharmapalan et al. for quantification of safety risks based on design alternatives [22], and many more tools are proposed [23–25]. However, it is still interesting to note that construction safety planning is generally carried out separately from execution [18] which results in lack of communication and generates problems for safety manger in assessing (how, when, what, where, and why) safety measures needed for accident prevention [19]. It is further observed that traditional safety planning in construction has been infrequent, manual, time-consuming, labor-intensive, and prone to human error by using two-dimensional (2D) paper drawings and reports [5, 19, 21, 25] during the construction phase of the projects. On these grounds, advancement and automation are required for the improvement of the existing 2D drawing-based manual safety management processes as well as early prevention in the design phase by using technologies.

This paper proposed a unique approach for automated safety excavation modeling approach compliance with safety regulations and best practices, leveraging visual programming and BIM technologies for safety management process. To identify the benefits and limitations of the proposed approach, a system prototype is developed and verified through a case study. More specific objective of the study is to develop an automatic BIM-based safety planning tool specific to the excavation in construction that can identify potential hazards related to fall, cave-ins, and safety egress along with a visualized 3D model with built-in preventive solution for recognizing hazards. This research work does not consider the entire hazards related to geotechnical activities at this stage. Hence, the scope of the study is limited to the major types of potential risks, including but not limited to cave-in, fall, and safety egress risks.

2. Safety Planning Practices and BIM Applications

With regard to understanding the current safety planning status in focused area, a deep review of the previous research studies is summarized as safety planning practices related to pits and trenches in construction industry. Insufficiencies in contemporary safety planning were contemplated herein with BIM-based advanced design for safety concepts. Research works on rule-based safety planning and BIM are thoroughly reviewed, and necessity of the proposed safety rule-based automated excavation modeling approach is established.

2.1. Safety Planning Practices for Excavation in Construction. Despite extensive research and technological advancement in the construction industry, still it is considered as a hazardous industry that exposes workers to accidents. Safe environment is mandatory in all industries, while in construction, it is of particular importance compared to other industries because of four times higher fatality rate [26]. Accident statistics related to excavation revealed a relative increase in injuries and fatalities in the last years [2], which makes the excavation safety planning challenging. Execution of bad safety planning consumes the financial resources and time ineffectively and sometimes causes severe accidents [18]. In order to enhance safety at construction sites, companies have been establishing strategies and rectifying construction methods to ensure health and safety, such as toolbox talks, regular safety planning meetings, owner's involvement in safety planning, etc. [8]. Several rules and best practices have been developed since Occupational Safety Health Act 1970 [16, 17] that can be categorized under three general groups: (1) preexcavation—procedures required prior of any digging task; (2) excavation—safety during the activity execution; and (3) post-excavation—processes required after completion of excavation [6]. Safety planning based on these regulations in the design and planning phase is cumbersome owing to the dynamic nature of excavation activity. Construction companies depend on perpetual manual observations of the safety managers, which is requisite by OSHA; besides, a competent person with relevant safety skills [27] has to visit frequently and examine site condition. This requirement sometimes causes inconvenience due to economic and time constraint; consequently, safety managers are not present when obligatory and thus accidents occur [4]. Furthermore, safety knowledge such as safety regulations and experience integration with the design phase could reduce or even eliminate related risks by suggesting proper consideration or even changes in the design [28]. The analysis of 224 accident cases depicts that 42 percent of fatalities were linked to risks associated with design phase [29]. As manual detection of unsafe design is difficult due to scattered regulations and complex nature of construction projects [18], designers are mostly unaware of the activity conditions and associated physical constraint during construction; consequently, designers feel vexation in determining risks associated with their design components that may arise at construction phases of the project [1]. Correspondingly, communication gap and limited cooperation of the stakeholders regarding construction safety curtail the safety culture [30]. Even though trench collapse has a notable impact on safety and causes a major portion of accidents in the construction industry, it is still undiscovered. However, Literature revealed a lack of concentration towards workers safety aspect in the preconstruction phase of excavation works. Overcoming these limitations and challenges is extremely important in order to ensure a safe working environment with minimum accident possibilities in excavation-related activities.

2.2. Rule Compliance BIM-Based Safety Planning Approaches. Building information modeling (BIM) transformed the way of planning, designing, construction, operation, monitoring, and controlling for building and infrastructure [18, 31–39]. Several procedures have been recommended recently by extensive research employing BIM and other advanced technologies in order to figure out the problem of manual safety planning in the construction industry [1, 5, 23, 28, 36]. Zhang et al. [19] proposed an automated approach to safety planning by integrating fall prevention rules with BIM model. Feng and Lu [25] used algorithmic modeling tool (dynamo) to automate scaffolding planning and their risk analysis in construction sites. Existing construction best practices and rules can be used in convergence with three-dimensional (3D) model to engender an automated checking system for safety rule [38]. Automated workspace visualization method was established by Zhang et al. [40], which proactively improves safety during construction by using workspace modeling technologies and remote sensing. Wang et al. [6] also used safety rules and range point clouds as a modeling technology to control excavation-related hazards during construction phase. A tool called "See-BIM" has been developed by Belsky et al. [41] that tests topological relationship and embeds new knowledge details about the model through compiling a set of rules. Studies have considered risk factors in the design phase that could avert construction accidents and developed automated BIM and safety rule-based unsafe designs in construction [18]. In past few years, extensive research has been carried out focusing on rule-checking algorithms and BIM applications in order to enhance existing safety culture, its processes, and procedures [42, 43]. Studies have confirmed the use of programming to formalize the algorithms. Program developers have currently options to exploit various tools and techniques such as Open C, Java, Python, visual programming or visual algorithmic modeling, etc. To exercise the advantages of such tools, BIM users are trying to extend the use of BIM to the early design stages by connecting their product directly or indirectly [44].

2.3. Need for an Automated Rule Compliance Safety Modeling in Excavation. The literature review revealed that researchers have focused either on excavation's safety monitoring and inspections [6, 8, 27] or on trench-related hazard analysis and mitigation planning during the construction phase [6]. Nevertheless, few tools for incorporating safety rules in the preconstruction phase of the project are limitedly available, while safety planning for excavation works in preconstruction phase is yet unstudied and needs to be investigated. In addition, incredible improvements in excavation safety performance have been reported in recent years. Chi and Caldas recently developed image-based safety system for surface mining and earth moving activities [45], yet, automated hazard visualized excavation's safety planning in preconstruction phase is still lacking. To date, none of the existing studies currently provide evidence of safety rules integration through algorithmic modeling tool in a BIM model. Even though there has been few studies focusing on safety enhancement in preconstruction phase [18, 19, 25, 30, 36, 38, 46], none of them focuses on excavation-related safety management that can support automated modeling. Hence, significant attention is required to investigate better visualization techniques and safety process automation. Proactive elimination of hazards can be possible if safety regulations related to each activates are appropriately considered at preconstruction phase. Applications of advance techniques are inevitable to integrate concerned regulations to each hazard for the purpose to ensure safety in excavation works. Therefore, additional innovative algorithmic modeling approaches are needed to be explored for the integration of construction safety rules and best practices with the BIM 3D model in preconstruction phase. With these needs in mind, the next section will propose a unique approach for BIM-based excavation safety rule compliance modeling that can support automated 3D modeling with proactive visualization of potential hazards.

3. Research Design and Framework

In order to understand the nature of hazards related to excavation, the study was commenced with a detailed study of accident cases and previous literature. Thereafter, present status of safety management, related safety rules established by OSHA, and state-of-the-art of BIM technologies were reviewed. Initial investigation of excavation work hazards identified in accident cases motivated the development of a conceptual framework for automated safety excavation modeling. Subsequently, system prototype was developed and implemented on a real-world case study in order to test system's usability and effectiveness.

The proposed approach as depicted in Figure 1 reflects the conceptual framework that deals proactively with cave-in, fall, and safety egress risks. The conceptual framework for BIM-based excavation safety rule compliance modeling approach comprises three parts. First, the extraction of relevant rules from the pool of construction industry best practices and regulations along with the other process guidelines and information that includes field test and blueprints. Second part consists of visual programming and BIM. The former is used to convert the required safety rules information to graphical algorithms in a single scripting environment while latter one is used to integrate the process to a common place. Similarly, the third part is composed of automated modeling tool, which executes safety rule algorithms on the acquired information from two-dimensional (2D) data drawings in a BIM platform. Commercially available BIM tool (in our case Revit) is used for the ultimate model generation and visualized protection plan with its quantitative estimates and optimized locations as shown in Figure 1.

4. Proposed Prototype System Based on Framework

Based on the methodology and framework given above, a proposed automated excavation safety modeling system is developed as a tool for rule compliance automated safety planning. This system is named as Auto-Exca Safety Modeling System, which comprised of the following three modules, namely, (1) information extraction and logic design (IELD) module; (2) information conversion and process integration (ICPI) module; and (3) automodeling and safety plan generation (ASPG) module. The functions and systematic process of the prototype system in each module are detailed in the following sections.

4.1. Information Extraction and Logic Design (IELD) Module. As the name indicates, the function of this module is to extricate information from the raw data. The information extraction and logic design (IELD) module is initiated with the analysis of OSHA regulations. These rules provide best practices and lesson learned in the construction industry. The IELD module focuses on the extraction of relevant information from the pool of OSHA regulations. These ejected relevant rules are then manually converted to mathematical logics and then further into computer readable data in the next module. As illustrated in Figure 2, additional required guidelines is also considered in this module, such as soil type and actual excavation dimensions would be input from the soil report and excavation's blueprints, respectively.

4.1.1. Extracting Relevant Safety Rules. Causation of accidents provides vital information for safety planning; historical data related to trench excavation were reviewed and analyzed to find out the major risks and causes. Collapse cave-ins, safety egress, machinery and human fall into the trench, and humans hit by machinery were the major potential risks identified during the accident cases investigation. Apart from that, other risks like oxygen deficiency inside the trench, fire, and water leakage were also reported. Among them, collapse cave-ins pose the greatest potential risk to the workers in excavation. To limit the scope, this study only considers the top three potential risks (cave-ins, safety egress, and fall). The rest of the remaining associated risks to excavation works are out of scope at this stage of the research. Standard prevention methods applicable to associated risks minimization and mitigation were thoroughly studied in the context of regulations (OSHA).

The OSHA described the regulation in three parts beside the appendices (Table 1). First, scope and definitions (Subpart P-Excavation 1926.650) discusses the terminologies and its application with scope. Second, excavation specific requirements (Subpart P-Excavation 1926.651) illustrates hazard information and required measures specifically linked to the excavation. The third part is protective system requirements and criteria (Subpart P-Excavation 1926.652), which further explains the second part that determines prevention criteria and protective system to be used. Moreover, 1926 Subpart P-Excavations also include six appendices such as appendix A to appendix F. In 1926 Subpart P, appendix A focuses on soil classification while appendix B describes sloping and benching details. This study considered both appendices (A and B) for sloping method and soil classification. In addition to that, 1926 Subpart P appendix C, appendix D, appendix E, and appendix F show the detailed procedure along with scope for timber shoring, aluminum hydraulic shoring, alternative to timber shoring, and graphic summary of requirements in Subpart P, respectively. Applicable rules to the top three risks were extracted. Sloping, benching, and shoring are the methods advised by OSHA regulations and several best practices to protect workers from cave-ins in excavation trench. This paper considers merely sloping method (1926.652(b)) based on the soil classification available in the regulations (1926 Subpart P App A-Soil Classification).

Table 2 shows the detailed information specific to the intended risks from OSHA website. According to OSHA 1926.652 (a) (1), "each employee in an excavation shall be

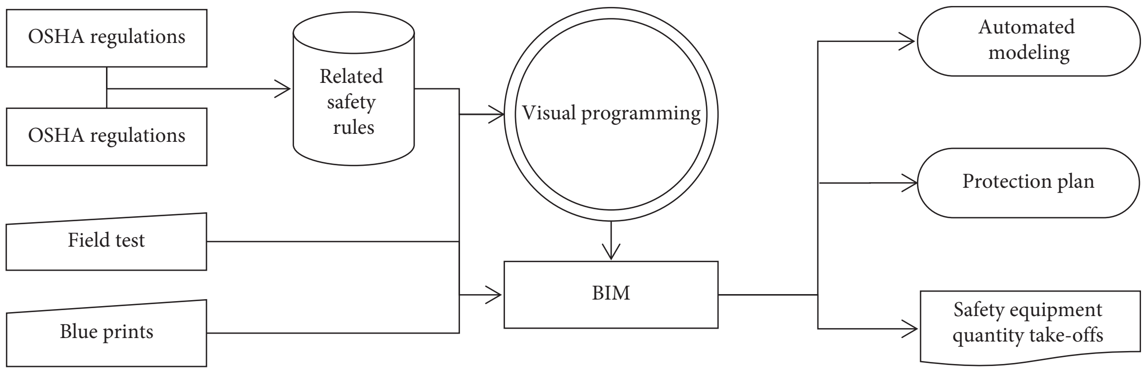


Figure 1: Conceptual framework for automated safety excavation modeling approach.

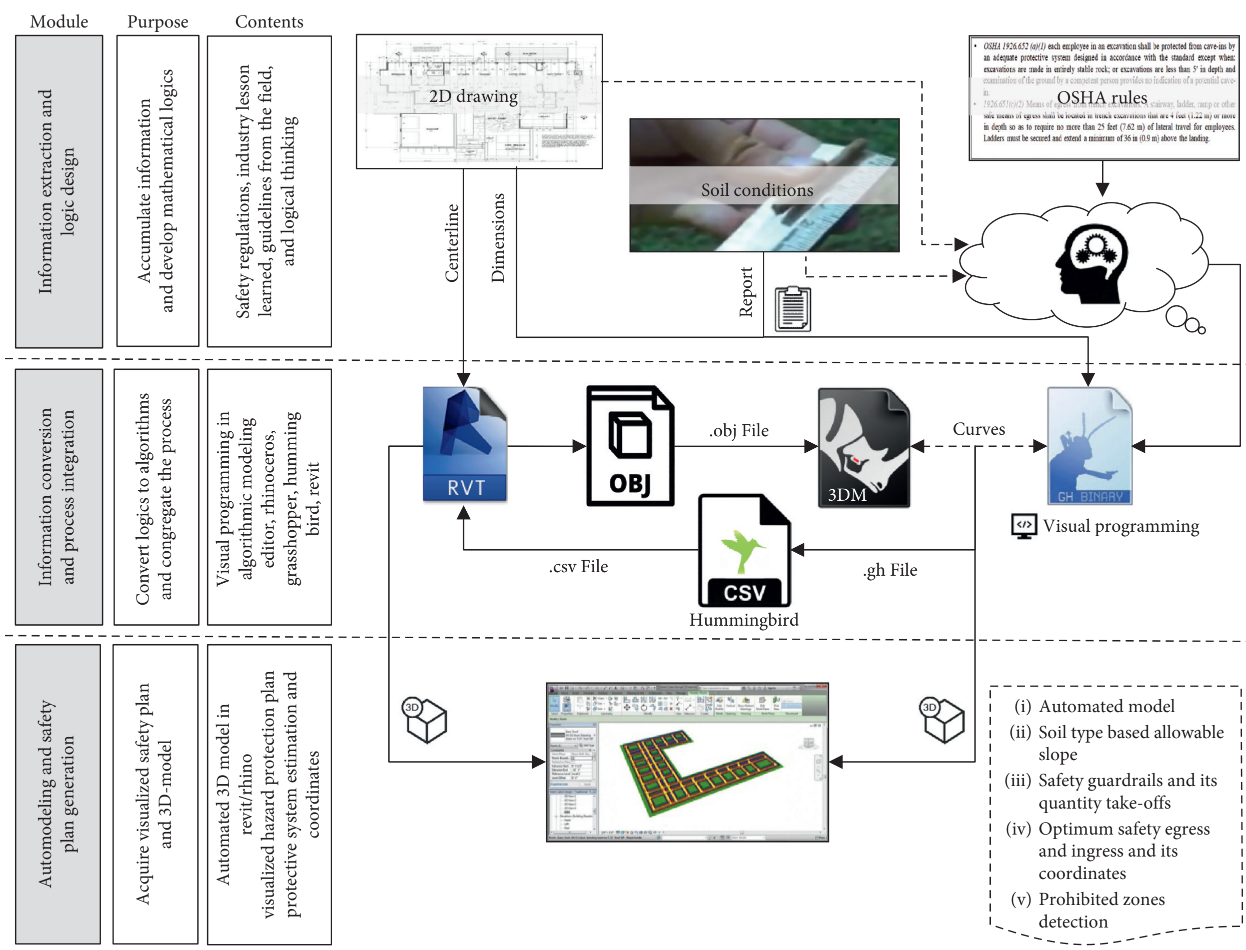


Figure 2: System architecture for auto-exca safety planning model approach.

protected from cave-ins by an adequate protective system designed in accordance with the standard except when excavations are made in entirely stable rock or excavations are less than 5′ in depth and examination of the ground by a competent person provides no indication of a potential cave-in." The standards state maximum allowable slope (horizontal to vertical ratio) for excavation pits considering the soil or rock properties (see Table 1).

Likewise, another rule 1926.651(j) (2) says workers will be protected from spoiled materials, excavated or other materials or equipments that could cause a hazard by rolling or falling into excavations. Protection shall be provided to the employees by placing that material and equipment at least 2 feet (0.61 m) away from the edge of excavation pits/trenches (Table 1), or by the using sufficient retaining devices that could prevent materials or equipment from falling or rolling into excavations, or combination of both conditions should be employed if necessary. Considering safe egress, the rule 1926.651(c) (2) clearly specifies the criteria for means of egress and ingress: stair, ramp, ladder, or other safe means of

Table 1: Excavation-related OSHA rules.

1926 Subpart P-Excavation		
No.	Standards	Explanation
1926.650	Scope, application, and definitions applicable to this subpart	Appraise terminologies and application guidelines
1926.651	Specific excavation requirements	Illustrates hazard information and required measures specifically linked to the excavation
1926.652	Requirements for protective systems	Further explains the second part that determines prevention criteria and system to be used
1926 Subpart P Appendix A	Soil classification	Focuses on soil and rock classification based on site, environmental conditions, and structural composition of the earth deposits
1926 Subpart P Appendix B	Sloping and benching	Describes sloping and benching if adopted as procedure to protect workers in excavations from cave-ins
1926 Subpart P Appendix C	Timber shoring for trenches	This appendix covers information if timber shoring is used as a method to protect employees from cave-ins
1926 Subpart P Appendix D	Aluminium hydraulic shoring for trenches	Appendix D contains information when aluminium hydraulic shoring is provided to protect workers against cave-ins
1926 Subpart P Appendix E	Alternatives to timber shoring	Alternative to timber shoring is illustrated in this appendix through figures
1926 Subpart P Appendix F	Selection of protective systems	This appendix explains the requirements for the protective equipment's used for less than 20 feet depth as summarized logical figures

Table 2: OSHA regulations related to excavation works.

Depth	Soil type	Slope ratio	Protection needed		
			Cave-ins	Safety egress	Fall
$D < 5$ ft	—	Vertical side 1 : 0	No	No	No
$5\text{ ft} < D < 20$ ft	Stable rock	Vertical side 1 : 0	No	Yes	Yes
	Type A	0.75 : 1	Yes	Yes	Yes
	Type B	1 : 1	Yes	Yes	Yes
	Type C	1.5 : 1	Yes	Yes	Yes
$D > 20$	—	Consult P.E	Yes	Yes	Yes

egress shall be provided in trench excavations that have depth equal to or more than 4 feet (1.22 m). Moreover, the location of that means of egress should be optimized in such a manner so that the employees require no more lateral distance than 25 feet (7.62 m). Ladders must be secured and extend a minimum of 36 in (0.9 m) above the landing. These rules provided knowledge for automation algorithms implemented in BIM. Specific steps taken for the automation are discussed in the next section.

4.2. Information Conversion and Process Integration (ICPI) Module. The information conversion and process integration (ICPI) module is the vital module of Auto-Exca Safety Modeling System. This module is devised to convert mathematical logics acquired through the IELD module into machine-readable format as revealed in Figure 2. To do this, visual programming techniques were employed. Commercially available tool, Grasshopper (a plug-in to Rhinoceros), which is a powerful tool for visual programming is selected for the development of visual scripts. This software is implemented in the study, mainly because it is relatively easy to use compared to other proprietary programming language software, is fast, and has diverse feature components required for this kind of programming. It is a platform that empowers designer to solve problems by visual programming and develop own tools. The humming bird was used for interoperability between the Grasshopper and other commercial BIM tool called Revit as delineated in Figure 2. It is used due to its broad functions and effectiveness for transferring more than one type of geometry. Functionality of Hummingbird plug-in covers a wide variety of different family types such as adaptive components, levels, walls, beams, lofts, and family instants and imports as CSV file to create geometry. A veritable tool file is developed from the algorithms created in a single scripting environment and then imported as CSV file to create geometry in a BIM (Revit) using Hummingbird available in both. The implementation of the prepared tool was executed in the next module.

4.3. Safety Rules-Based Visual Algorithms Development. This section focuses on the process details of the transformation of mathematical logics to algorithms through visual programming tool (Rhino Grasshopper). This commercial software provides visual scripting process in terms of predefine functionality components and wire connections for inputs and outputs data.

As noticed in swimlane diagram, Figure 3, there are four main portions that are cave-ins, prohibited zone, fall, and safety egress. First, in the cave-ins section, the system will convert logically designed rule for allowable slopes required for different types of soil. This is then ultimately liable to design proactive measure for cave-ins risk, in this case sloping base on soil types as shown in Figure 4. Second, with respect to prohibited zone, previous algorithm would be extended to figure out the danger zone near the edges. Third, with reference to the previous two algorithms, guardrail would be established for fall risk. Fourth, an additional algorithm for safety egress would be incorporated with the first section on the designated centerline.

4.3.1. Cave-In Hazard. As discussed earlier, cave-in is the major type of accident and usually happens in the excavation-related projects. Figure 5 deliberates the developed visual program to recognize the potential risks of cave-in and then suggests a preventive solution in 3D through slope ratio or angle based on the soil classification in OSHA standards. Figure 3 swimlane diagram shows the process flow of programming for cave-ins risk in the first column. To determine the bottom width, offset the centerline from inside and outside depending on the dimension input as shown in Figure 6 by using Voronoi logic tool imported to the Grasshopper canvas.

The offset curves inside and outside to the centerline at the specified distance and direction can be added by using Python Script Editor > import rhinoscriptsyntax as rs > a = rs.OffsetCurve(curve, dir, dis) in Grasshopper, where "rs" is the rhino-script and "a" refers to the output offset curves to the centerline at a given direction and distance.

In pursuit to understand the obligation of the excavation preventive procedures, the depth related OSHA rule 1926.652 (a) (1) (see Table 2) was translated through an algorithm. Afterwards, to detect the slope ratio or angle of the excavation, mathematical equation was generated and scripted as follows:

$$\mathrm{W.T} = (D * 2) * \mathrm{SR} + W, \qquad (1)$$

where W.T is width at the top of the excavation, SR is a slope ratio of the soil type based on the classification, and D and W refer to the given depth and width for trench, respectively. The depth and width can be identified from the 2D blueprints, while the slope ratio can be extracted from the field test. Table 1 and Figure 4 describe four types of soil along with maximum allowable slope from regulations. Notice that angle (α) equal to 90° is allowed in excavation pit and safety prevention is not required in cases of stable rock. However, slope angle (α) equal to 53°, 45°, and 34° is required for rest of the remaining three types of soil, type A, type B, and type C, respectively. OSHA further clarifies that if the field test result of the soil type is absent, then soil type C will be used for further actions to ensure safe side [12]. The presented algorithm in Figure 5 will automatically visualize cave-in hazards determined by abovementioned soil type.

4.3.2. Fall Hazard. Falls from heights have received keen attention of health and safety management professionals and academic researchers. Currently, construction industry professionals are doing manual estimation and modeling of fall protections. This manual process needs a great deal of human inputs and cost and consumes time. However, some researchers used automated modeling for fall protection [19, 23, 38]. To automate and advance the safety management process with respect to fall risk in excavation works, an attempt was made to sort out the issue of automated modeling and estimation approach for fall preventions.

The programming process flow applied to detect edges where fall might happen and produce guardrails right there is depicted in Figure 3. The slope edges are defined in first column and are extended to the second column in the interest of prohibited zones; thereupon, guardrails are established in the process at third column of swimlane diagram. Previously stated fall hazard-related OSHA standards (see Table 2) are converted to graphical algorithms as illustrated in Figure 7. According to OSHA regulations, if the depth from the surface to the lower level exceeds than 6 feet, then fall protection system is needed. In addition, another vital rule for prohibited zone ascertaining to avoid overturning of the heavy construction machinery or human into the trench was also incorporated into the script (see Figure 7). That rule recommends that there will be prohibited zone for human, material, and machinery of at least 3 feet from the edge of the affected zone. Hence, the algorithm was set to allocate the fall prevention at the distance of 3 feet and visualize the prohibited zone along with the quantity of guardrails in running length.

4.3.3. Safety Egress. Numerous ways are currently used in the real construction excavation sites to ensure safe access. Apparent methods are providing slip-resistant ramps, use of stairs/ladders, and stepping back an excavation. OSHA standards endorse the provision of means of egress and ingress to the trench excavation if the depth is equal to or greater than 4 feet. The furthest lateral distance of the egress point from any worker inside the trench excavation should not be greater than 25 feet. Figure 8 demonstrates the algorithm for location optimization for means of egress and ingress.

The centerline of the excavation obtained from 2D blueprints (Figure 9(a)) was taken as a reference for optimized spot location as depicted in swamlane diagram in Figure 3. To calculate the most favorable points, a grid of 5 feet by 5 feet was positioned through a visual programming script as shown in Figure 9(b). Unique points of 25 intervals were picked through using the cull pattern for every five points (green points in Figure 9(c)). Next, the circles of 25 feet diameter were embedded on those unique points in order to trace the overlapping regions. The midpoints in overlapping regions of the two circles were then considered as an optimum location for means of

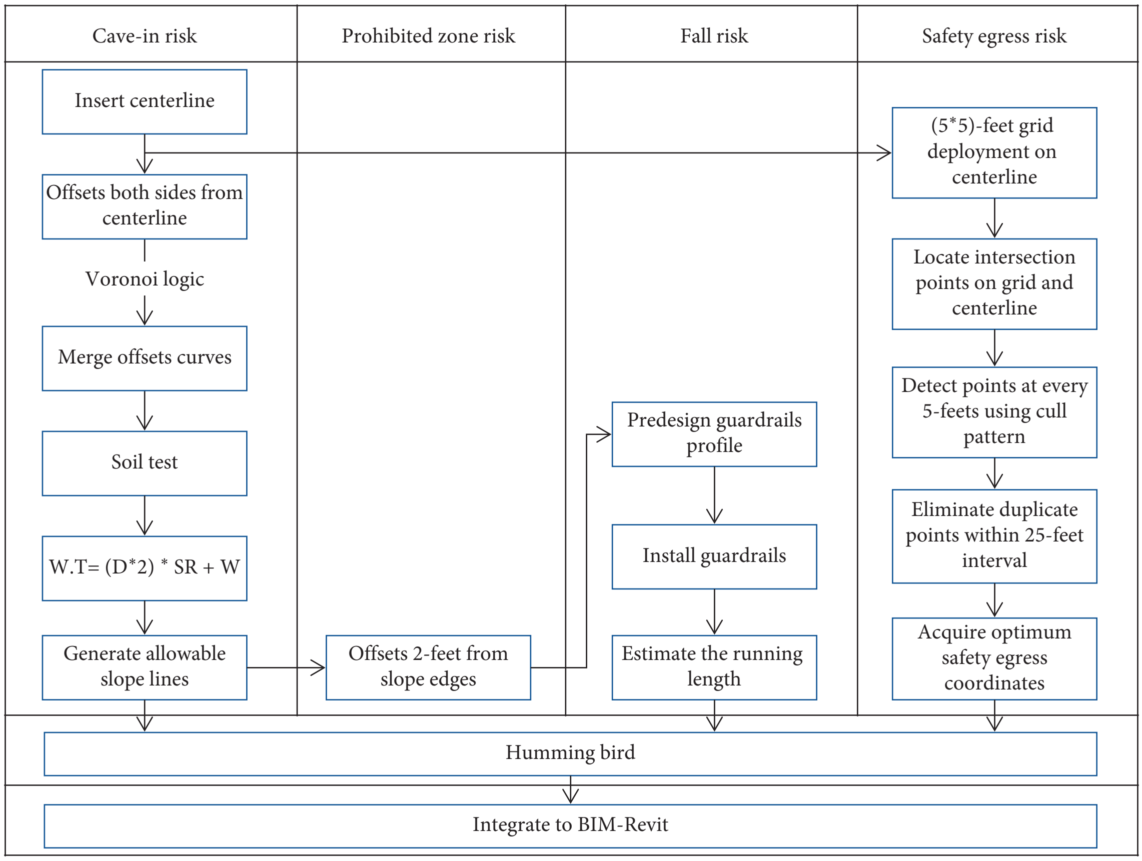


Figure 3: Visual algorithm development swimlane diagram.

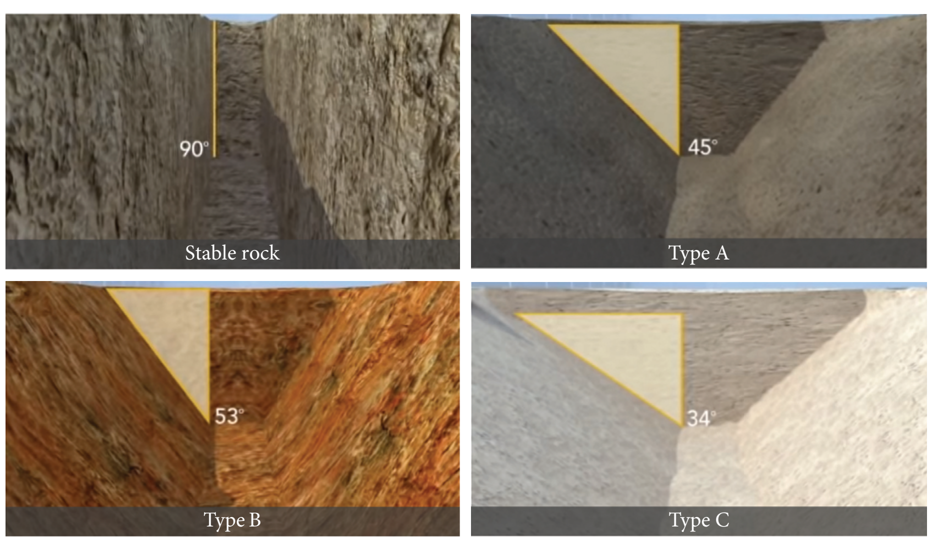


Figure 4: OSHA prevention videos (v-tools) for excavation.

safety egress and ingress. Finally, the system will provide a chart after simulation that shows the exit number of required safe access locations along with the position coordinates. The entire three portions of algorithm scripts were then connected to each other to make a complete, comprehensive visual program for Auto-Exca Safety Modeling System.

4.4. Automodeling and Safety Plan Generation (ASPG) Module. Lastly, the function of this module is to produce results after information extraction and logic design (IELD) and information conversion and process integration (ICPI) modules. The automodeling and safety plan generation (ASPG) module is designed to give users the visualized outcomes, produce an automated safety plan, and determine

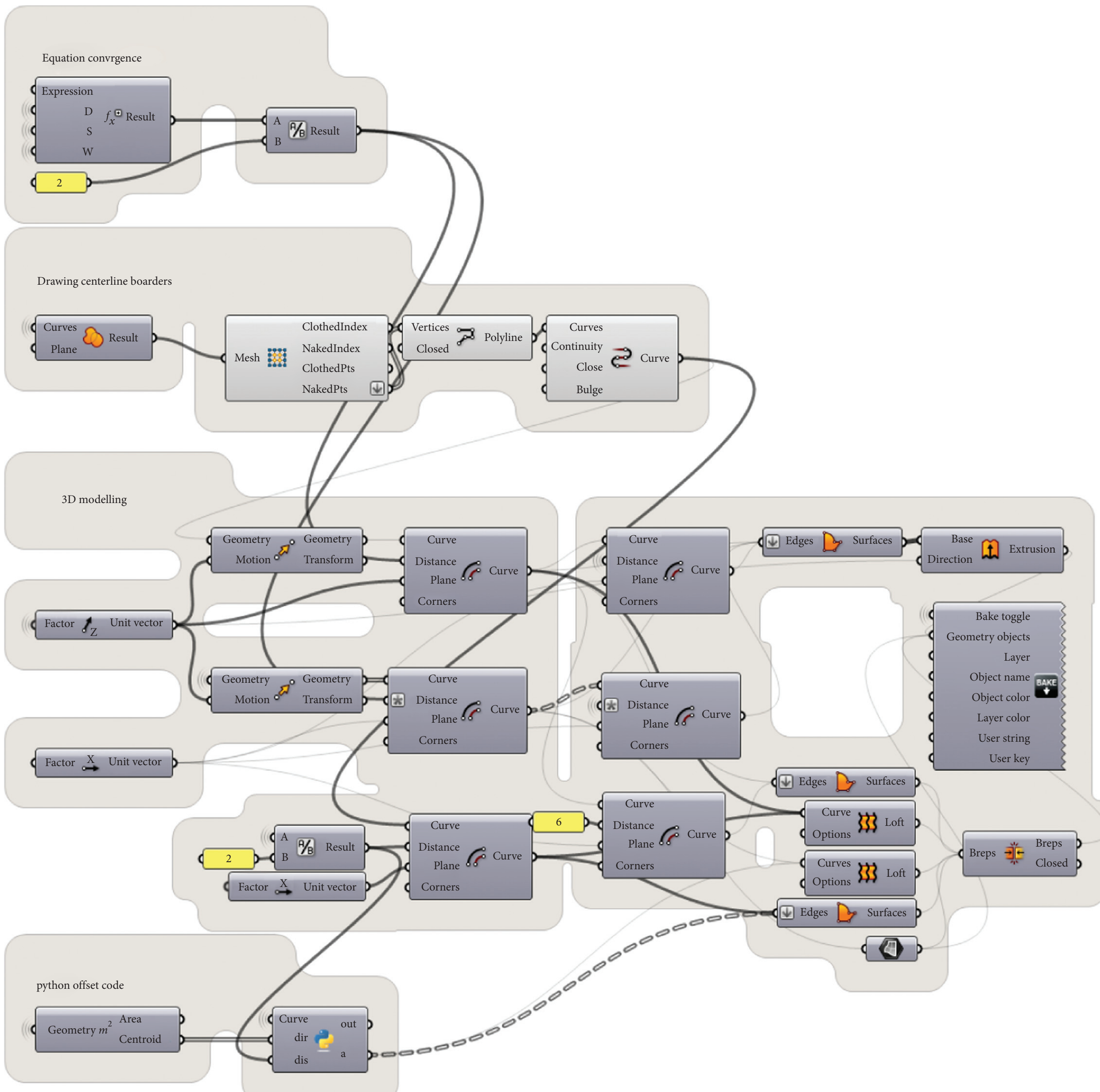


Figure 5: Cave-in hazard identification and preventive measure algorithm.

hazard response strategies. The principal emphasis of this module is to execute the developed tool on any centerlines of a given excavation 2D plan, which could be obtained from the excavation blueprints. The users select the soil types and feed the actual required width and depth, and then the simulation is conducted. The potential of this module is the rule compliance 3D model automatic safety plan for possible hazards. Detailed functions and results of the ASPG module are categorically illustrated in the discussion section.

5. Case Study

This section demonstrates a case study conducted to validate the prototype system by using a real-world excavation project. The aim was to apply Auto-Exca Safety Modeling System tool developed for automated safety planning and modeling with regard to excavation pits on a practical building project. This project uses excavation trenches for making the foundation of the typical school building (Figure 10).

The 2D drawing made in Revit for foundation excavation was used for experiment (Figure 10). The centerline length, width, and depth of the foundation were obtained from the 2D drawings as shown in Figure 11.

The soil test from the field was assumed as type C soil. The acquired centerlines of foundation were then imported into Rhinoceros as object file (obj). With noticing that the location/scale of the file imported as .obj file should remain as default in Rhinoceros because the coordinates (x, y, z) of each vertex (points) are matching between Rhinoceros and

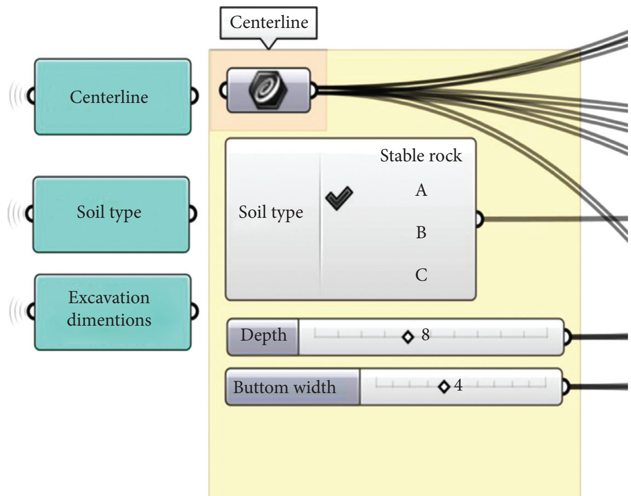


FIGURE 6: Soil classification and dimension constraint algorithm.

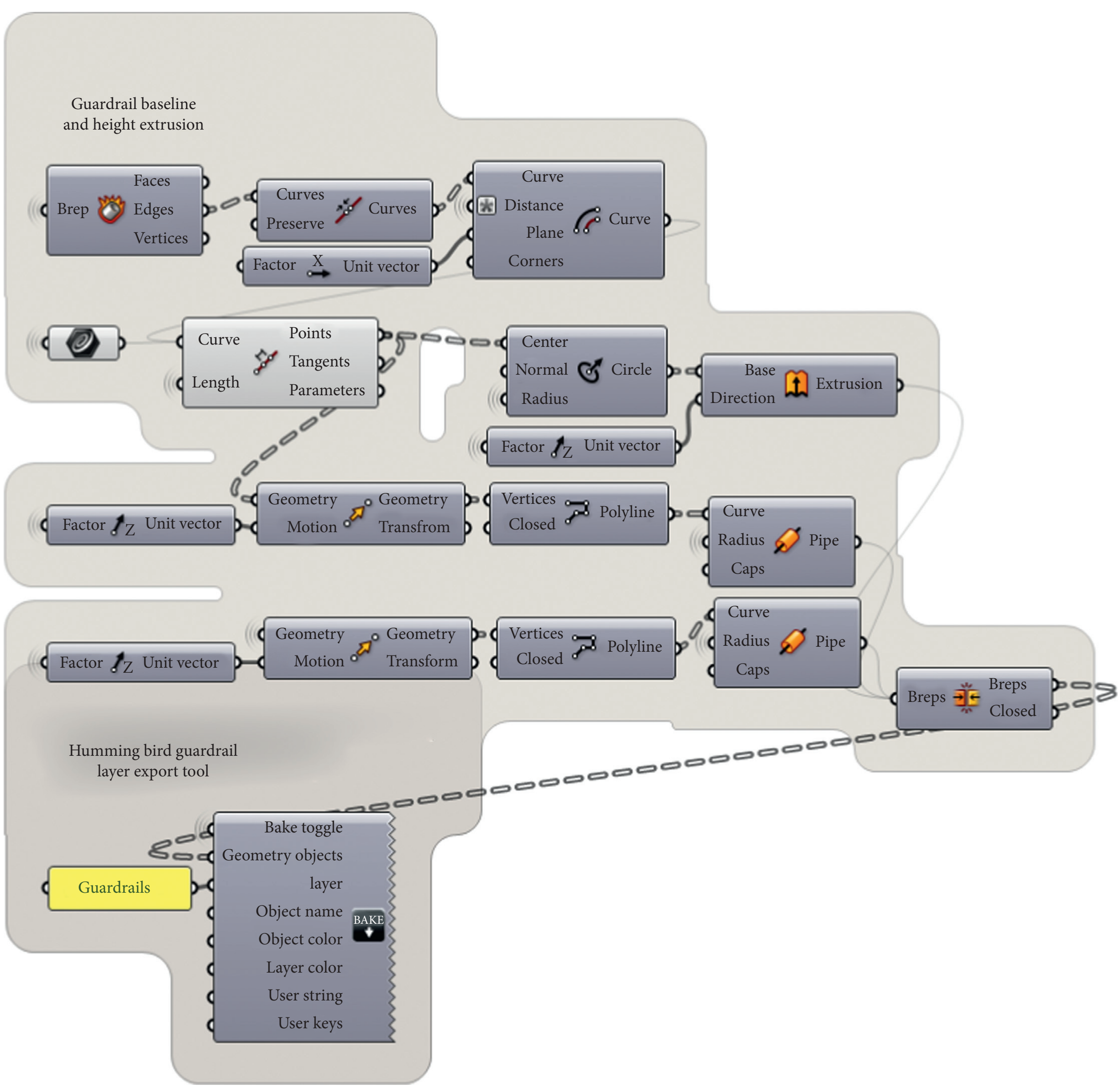


FIGURE 7: Algorithm for detecting fall hazards and required preventive solution estimation.

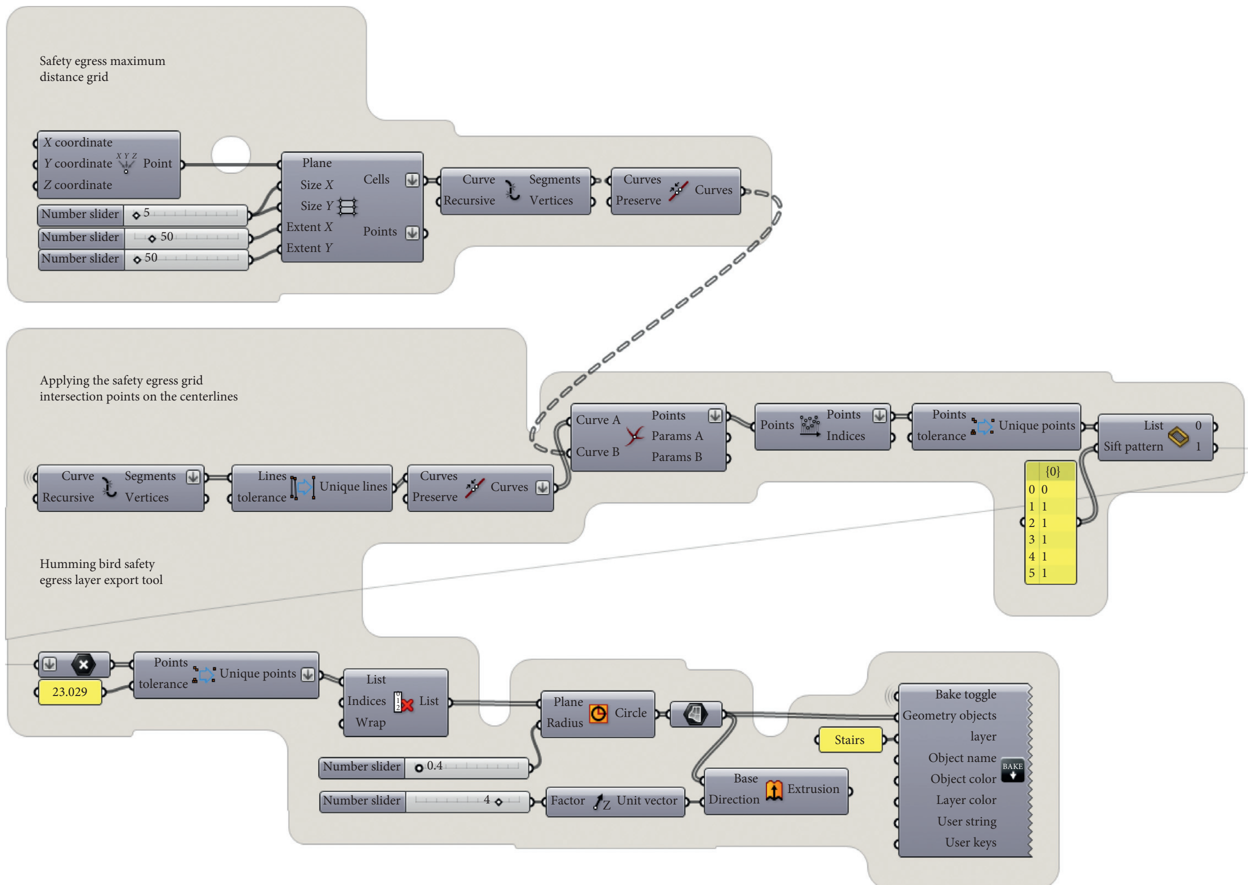
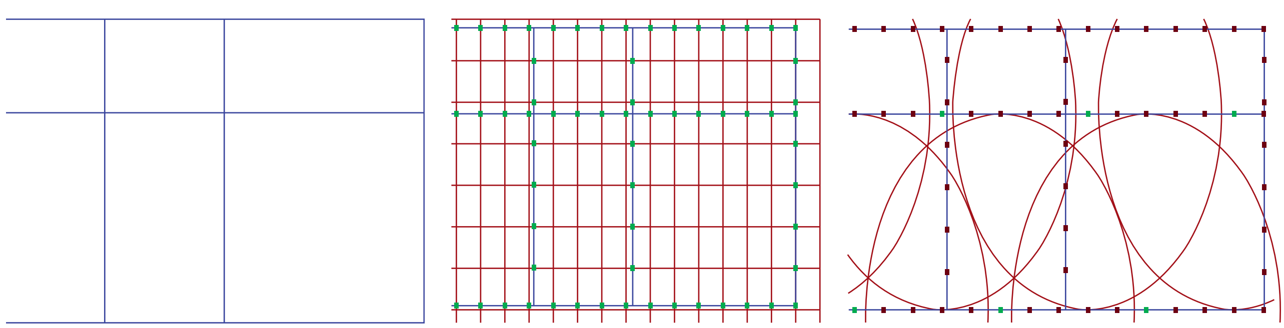


Figure 8: Algorithm for detecting optimized safety egress locations.



(a) (b) (c)

Figure 9: Safety egress algorithm process logics: (a) centerline from the 2D blueprints; (b) grid of 5 feet by 5 feet; (c) cull pattern for every five points and circle of 25 feet diameter.

Revit. If the coordinates (x, y, z) change, then as a result, the location/scale of the simulated foundation excavation model will not match with original 2D foundation layers. Formerly prepared graphical computational algorithms in grasshopper canvas were then simulated on the loaded data from the Revit into the Grasshopper. It was observed that the system produced the results successfully as expected for cave-ins, prohibited zone, fall and, safety egress risks. The brief result of the case study can be depicted in Figure 12. A 3D model was generated automatically with the appropriate allowable slope angle of 34° recommended by OSHA standards for type C soil. The generated allowable slope for the foundation trench can be seen through a cross section in Figure 12. In addition, the system automatically established guardrail system at the distance of 3 feet from the trench edges along with the estimated running length report (see Figure 13). The 3 feet distance between the guardrail system and the excavation trench edges are identified as a prohibited zone for machinery, spoil materials, and humans. Identification of this zone at this stage can decrease the occurrences of accidents due to the overturning of heavy construction machinery falling into the trench. In a similar manner, the

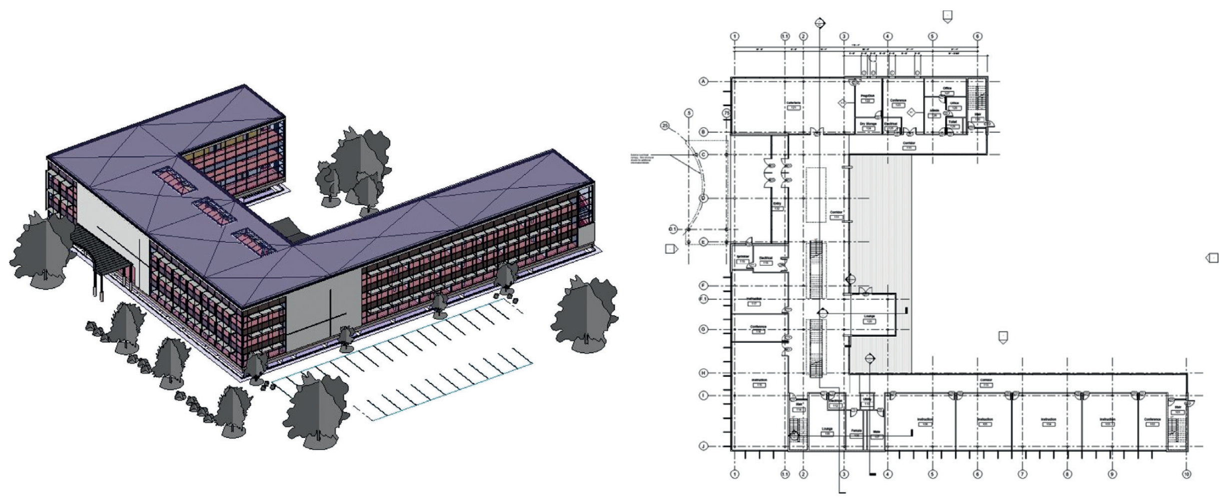


Figure 10: Isometric view and foundation plan of school building.

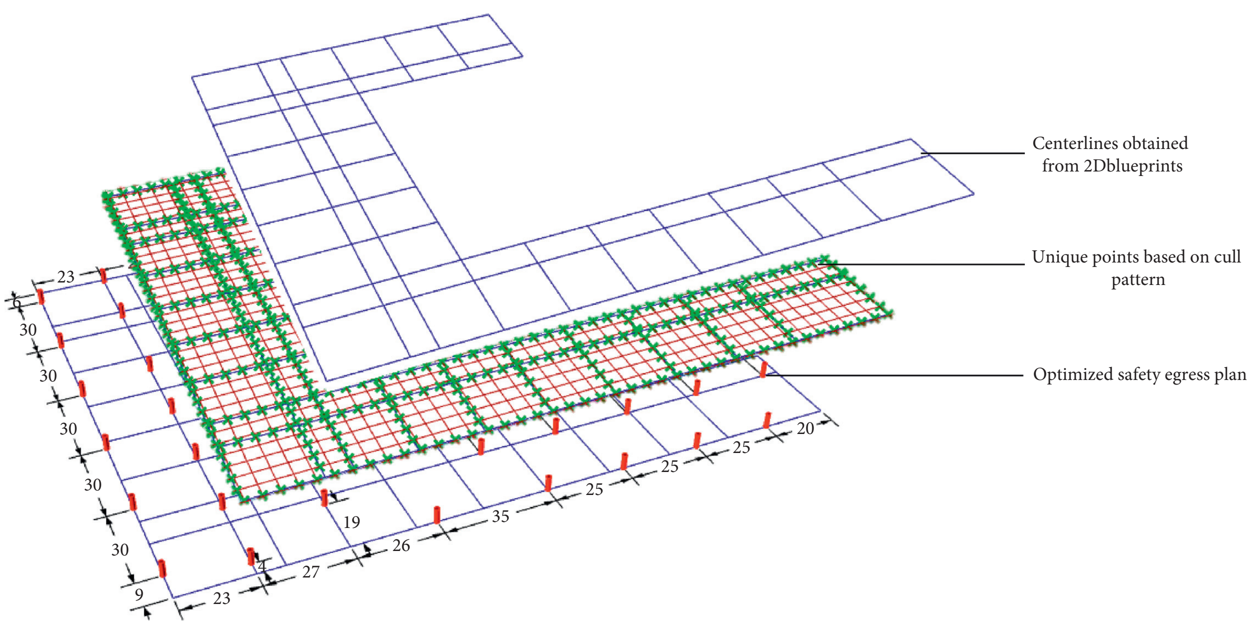


Figure 11: Automated excavation safety planning simulation.

automatically created 3D model correspondingly visualized an optimum safety egress plan for employees working inside the trench.

6. Discussion

The case study test of building foundation excavation revealed that the proposed system leveraging BIM technology could support more advanced and comprehensive excavation pits and trench safety planning. The tool has automatically and successfully designed the excavation slope according with the OSHA guidelines in order to prevent the cave-ins risk. The system produces more practical results when it comes to the contiguous trench; if the nearest alongside trench is close enough so that the slope lines intersect each other, in that case, the system generates more practical 3D model by visualizing both the trench as one pit. Notice that when this case happens in real construction site, the decision makers recommend excavating both the adjacent trench completely to avoid a potential collapse. The developed tool further detects vulnerable edges that could lead to fall risk and installed guardrails around the perimeter of the trench or pit. In addition to detection of edges and installation of guardrails, quantity take-off report list can be easily obtained by using its built-in function. OSHA made videos for education and training for concerned stakeholders in order to make the excavation works possible without accidents. The screenshots of the video made by OSHA for allowable slopes based on soil types can be seen in Figure 4. The framework for experiential safety education utilizing mobile-based virtual reality and augmented reality [47] can be extended to a comprehensive excavation safety training and education by integrating 3D model of the proposed system.

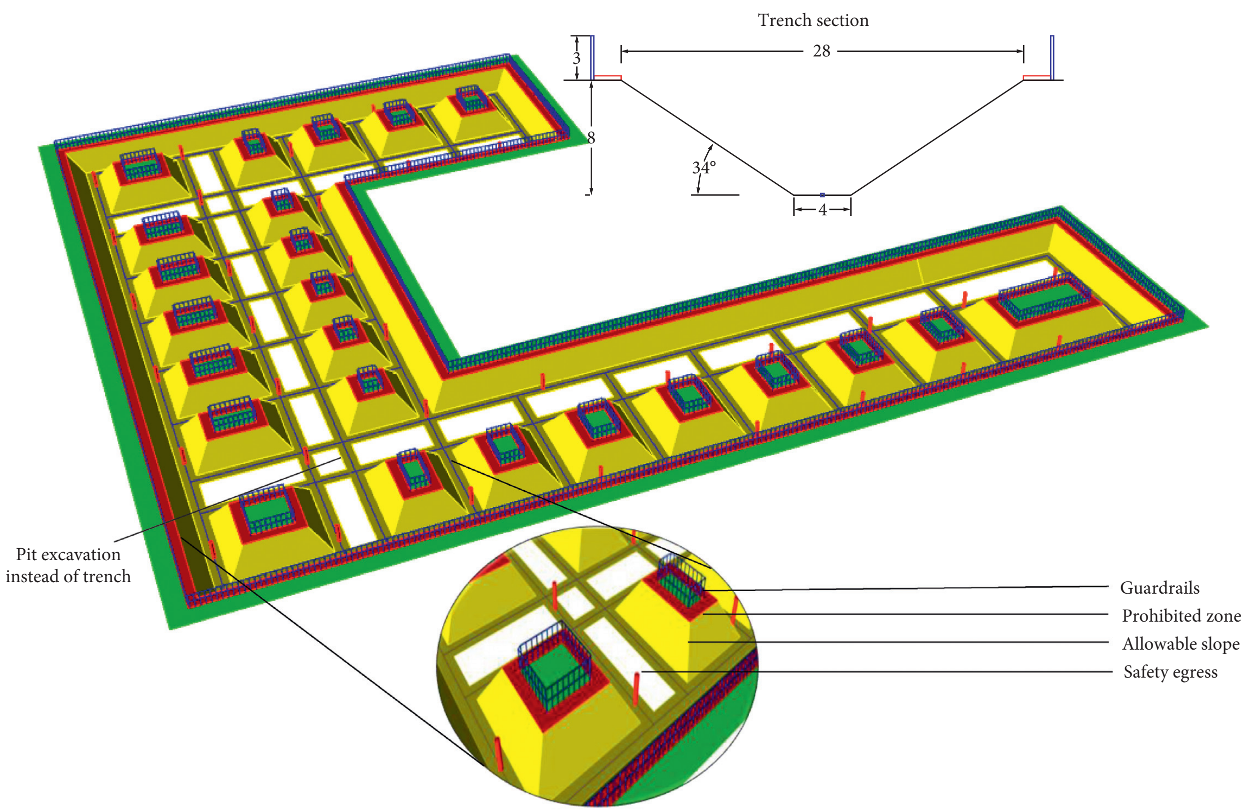


Figure 12: Automated safety planning model.

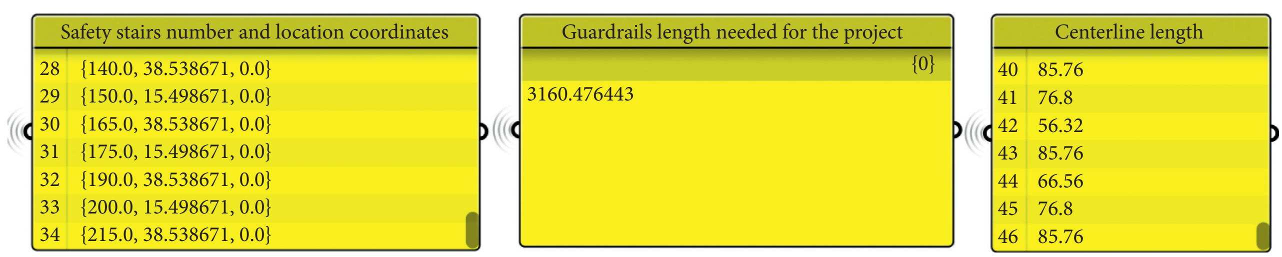


Figure 13: Quantity take-offs statistics chart.

The construction excavation is a dynamic activity that relies on different external factors such as weather (rain and hot temperature) and internal factors, for example, suffocation, toxic gases, water leakage, and underground services. Hence, representation of all unsafe conditions related to excavation pits and trenches in BIM at this level is not possible. Nonetheless, human hit by heavy machinery risk in construction excavation could be dealt with using 4D-BIM and sequencing the work path for both human and machinery considering their work schedule. Various limitations of the excavation's safety planning tool were observed through a building foundation case study. Several limitations of the system found were (1) that it might not be possible to generate required rule compliance 3D model for distinct layer of soil, since the layer of soil can vary based on the depth and width and (2) that as a construction site needs walkways crossing and pedestrian overpasses on trenches, this system does not specify crossings at current extent of study; however, users can modify the 3D model manually to overcome this limitation.

7. Conclusion

Despite the vital development of building information modeling (BIM) technologies for construction safety planning, current excavation safety planning practice is still manual and relies on conventional methods. To address the issue, an automated excavation safety planning tool was developed and tested. Based on the findings, the vital benefits are summarized as follows:

(a) The study depicted that the developed tool has ample potentials to enhance excavation-related safety planning, which is inevitable to cope with the recently reported significant increase in injuries and fatalities. It is found that the system automatically identifies and visualizes cave-ins, fall risks, and prohibited zone risks and optimizes the planning for ingress and egress based on OSHA rules.

(b) Automatic 3D model generation and more practical safety planning is another major contribution of this study. It is expected that the proposed approach would help the designers through automated modeling and assist decision makers in developing practical safety plans compared to the conventional 2D plans for excavation works at preconstruction phase. This unique approach of automatic modeling can be extended to other rule-dependent subjects and infrastructure work like bridges, pipelines, and additional works as parametric designs.

(c) Safety resources installation along with their quantity take-off and optimized locations were also witnessed in the case study. Hence, the system can predict the location coordinates and required preventive resources in advance.

To sum up, the potential of the VPL and BIM for the excavation safety planning and modeling at the preconstruction stage has been ascertained and confirmed with a real case study. In the future, this tool can be developed as a tab plug-in to commercial software applications that will enhance the entire safety planning process. Another future consideration is to simplify this tool to an app that can assist and guide field workers to execute safety plans in a more accurate and efficient way. Also, integrating the presented work with augmented reality could provide new direction for execution of planned excavation work in the real site. Moreover, this can be used to guide and educate the workers during the excavation execution phase.

Data Availability

The data generated or analyzed during the study are available from the corresponding author upon request.

Disclosure

The authors are solely responsible for the content.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (no. NRF-2016R1A2B3016694) and by the Chung-Ang University research grant in 2017.

References

[1] M. A. Hossain, E. L. S. Abbott, D. K. H. Chua, T. Q. Nguyen, and Y. M. Goh, "Design-for-safety knowledge library for BIM-integrated safety risk reviews," *Automation in Construction*, vol. 94, pp. 290–302, 2018.

[2] S. Hedmond, *Trench Collapse Deaths Have More Than Doubled in 2016*, Construction Junkie, Manhattan, NY, USA, 2017.

[3] T. Katsumi, "Soil excavation and reclamation in civil engineering: environmental aspects," *Soil Science and Plant Nutrition*, vol. 61, no. 1, pp. 22–29, 2015.

[4] Occupational Safety and Health Administration, *Trenching and Excavation Safety*, Washington, DC, USA, 2018, https://www.osha.gov/Publications/trench_excavation_fs.html.

[5] R. Hussain, D. Y. Lee, H. C. Pham, and C. S. Park, "Safety regulation classification system to support BIM based safety management," in *Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC 2017)*, International Association for Automation and Robotics in Construction, Taipei, Taiwan, June 2017.

[6] J. Wang, S. Zhang, and J. Teizer, "Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling," *Automation in Construction*, vol. 49, pp. 250–261, 2015.

[7] K. Slowey, *Trench and Excavation Fatalities Rise, Regulators Prioritize Safety*, Construction Dive, Washington, DC, USA, 2018, https://www.constructiondive.com/news/trench-and-excavation-fatalities-rise-regulators-prioritize-safety/520127/.

[8] C. Arboleda and D. Abraham, "Fatalities in trenching operations—analysis using models of accident causation," *Journal of Construction Engineering and Management*, vol. 130, no. 2, pp. 273–280, 2004.

[9] M. M. E. Zumrawi and A. El-Amin, "Importance of deep excavation support and its influence on adjacent buildings," in *Proceedings of the 7th Annual Conference for Postgraduate Studies and Scientific Research Basic Sciences and Engineering Studies—University of Khartoum*, vol. 6, pp. 25–29, Friendship Hall, Khartoum, Sudan, March 2016.

[10] National Institute for Occupational Safety and Health, *Preventing Worker Deaths from Trench Cave-Ins*, National Institute for Occupational Safety and Health, Washington, DC, USA, 2011, http://www.cdc.gov/mmwr/preview/mmwrhtml/.

[11] B. A. Plog, B. Materna, J. Vannoy, and M. Gillen, *Strategies to Prevent Trenching-Related Injuries and Deaths*, The Center to Protect Workers' Rights, Silver Spring, MD, USA, 2006.

[12] Occupational Safety and Health Administration, *Safety and Health Topics—Trenching and Excavation*, Occupational Safety and Health Administration (OSHA), Washington, DC, USA, 2018, https://www.osha.gov/SLTC/trenchingexcavation/.

[13] Bureau of Labor Statistics, *Census of Fatal Occupational Injuries (CFOI)—Current and Revised Data*, Bureau of Labor Statistics, Washington, DC, USA, 2017, https://www.bls.gov/iif/oshcfoi1.html/.

[14] Q. T. Le, A. Pedro, and C. S. Park, "A social virtual reality based construction safety education system for experiential learning," *Journal of Intelligent & Robotic Systems*, vol. 79, no. 3-4, pp. 487–506, 2015.

[15] S. Hedmond, *OSHA Identifies Trenching and Excavation Hazard Reduction as Priority Goal for 2018*, Construction Junkie, Manhattan, NY, USA, 2018.

[16] S. Choe and F. Leite, "Construction safety planning: site-specific temporal and spatial information integration," *Automation in Construction*, vol. 84, pp. 335–344, 2017.

[17] B. Esmaeili and M. R. Hallowell, "Diffusion of safety innovations in the construction industry," *Journal of Construction Engineering and Management*, vol. 138, no. 8, pp. 955–963, 2012.

[18] G. Hongling, Y. Yantao, Z. Weisheng, and L. Yan, "BIM and safety rules based automated identification of unsafe design

factors in construction," *Procedia Engineering*, vol. 164, pp. 467–472, 2016.

[19] S. Zhang, J. Teizer, J.-K. Lee, C. M. Eastman, and M. Venugopal, "Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules," *Automation in Construction*, vol. 29, pp. 183–195, 2013.

[20] W. Zhou, J. Whyte, and R. Sacks, "Construction safety and digital design: a review," *Automation in Construction*, vol. 22, pp. 102–111, 2012.

[21] J. A. Gambatese, J. W. Hinze, and C. T. Haas, "Tool to design for construction worker safety," *Journal of Architectural Engineering*, vol. 3, no. 1, pp. 32–41, 1997.

[22] V. Dharmapalan, J. A. Gambatese, J. Fradella, and A. M. Vahed, "Quantification and assessment of safety risk in the design of multistory buildings," *Journal of Construction Engineering and Management*, vol. 141, no. 4, pp. 1–9, 2014.

[23] T. Cooke, H. Lingard, N. Blismas, and A. Stranieri, "ToolSHeD™," *Engineering, Construction and Architectural Management*, vol. 15, no. 4, pp. 336–351, 2008.

[24] W. Suyoto, A. Indraprastha, and H. W. Purbo, "Parametric approach as a tool for decision-making in planning and design process: case study—office tower in Kebayoran Lama," *Procedia—Social and Behavioral Sciences*, vol. 184, pp. 328–337, 2015.

[25] C. W. Feng and S. W. Lu, "Using BIM to automate scaffolding planning for risk analysis at construction sites," in *Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC 2017)*, pp. 610–617, International Association for Automation and Robotics in Construction, Taipei, Taiwan, June 2017.

[26] Building Education, *Why Health and Safety Is So Important in Construction*, Building 4 Education, Bristol, UK, 2018, https://b4ed.com/Article/why-health-and-safety-is-so-important-in-construction.

[27] Center for Disease Control and Prevention, "Occupational fatalities during trenching and excavation work—United States, 1992–2001," *Morbidity and Mortality Weekly Report*, vol. 53, no. 15, pp. 311–314, 2004.

[28] M. Kasirossafar and F. Shahbodaghlou, "Building information modeling for construction safety planning," in *Proceedings of the 2012 International Conference on Sustainable Design, Engineering, and Construction*, pp. 1017–1024, Fort Worth, TX, USA, November 2012.

[29] M. Behm, "Linking construction fatalities to the design for construction safety concept," *Safety Science*, vol. 43, no. 8, pp. 589–611, 2005.

[30] K. Kim and J. Teizer, "Automatic design and planning of scaffolding systems using building information modeling," *Advanced Engineering Informatics*, vol. 28, no. 1, pp. 66–80, 2014.

[31] P. Li, S. Zheng, H. Si, and K. Xu, ""Critical challenges for BIM adoption in small and medium-sized enterprises : evidence from China," *Advances in Civil Engineering*, vol. 2019, Article ID 9482350, 14 pages, 2019.

[32] J. Franco, F. Mahdi, and H. Abaza, "Using building information modeling (BIM) for estimating and scheduling, adoption barriers," *Universal Journal of Management*, vol. 3, no. 9, pp. 376–384, 2015.

[33] P. Patlakas, A. Livingstone, R. Hairstans, and G. Neighbour, "Automatic code compliance with multi-dimensional data fitting in a BIM context," *Advanced Engineering Informatics*, vol. 38, pp. 216–231, 2018.

[34] J. Mukkavaara, G. Jansson, A. Holmberg, and M. Sandberg, "Approach for automated planning using 5D-BIM," in *Proceedings of the 33rd CIB W78 Conference 2016*Brisbane, Australia, October 2016.

[35] M. M. Singh, A. Sawhney, and V. Sharma, "Utilising building component data from BIM for formwork planning," *Construction Economics and Building*, vol. 17, no. 4, pp. 20–36, 2017.

[36] K. Kim, Y. Cho, and K. Kim, "BIM-driven automated decision support system for safety planning of temporary structures," *Journal of Construction Engineering and Management*, vol. 144, no. 8, article 04018072, 2018.

[37] M. D. Martínez-Aires, M. López-Alonso, and M. Martínez-Rojas, "Building information modeling and safety management: a systematic review," *Safety Science*, vol. 101, pp. 11–18, 2018.

[38] S. Zhang, K. Sulankivi, M. Kiviniemi, I. Romo, C. M. Eastman, and J. Teizer, "BIM-based fall hazard identification and prevention in construction safety planning," *Safety Science*, vol. 72, pp. 31–45, 2015.

[39] F. Muñoz-La Rivera, J. Vielma, R. F. Herrera, and J. Carvallo, "Methodology for building information modeling (BIM) implementation in structural engineering companies (SEC)," *Advances in Civil Engineering*, vol. 2019, Article ID 8452461, 16 pages, 2019.

[40] S. Zhang, J. Teizer, N. Pradhananga, and C. M. Eastman, "Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning," *Automation in Construction*, vol. 60, pp. 74–86, 2015.

[41] M. Belsky, R. Sacks, and I. Brilakis, "Semantic enrichment for building information modeling," *Computer-Aided Civil and Infrastructure Engineering*, vol. 31, no. 4, pp. 261–274, 2016.

[42] U. T. Petronas, "Development of BIM-based safety management model focusing on safety rule violations," in *Proceedings of the MATEC Web of Conferences ICCOEE 2018*, vol. 230, pp. 1–6, Le Mans, France, July 2018.

[43] M. Mekawy and F. Petzold, "Bim-based model checking in the early design phases of precast concrete structures," in *Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia*, vol. 2, pp. 71–80, Hong Kong, China, May 2018.

[44] W. Wahbeh, "Building skins, parametric design tools and BIM platforms," in *Proceedings of the 12th Conference Advanced Building Skins*, pp. 1104–1111, Bern, Switzerland, October 2017.

[45] S. Chi and C. H. Caldas, "Image-based safety assessment: automated spatial safety risk identification of earthmoving and surface mining activities," *Journal of Construction Engineering and Management*, vol. 138, no. 3, pp. 341–351, 2012.

[46] K. Kim, A. M. Asce, Y. K. Cho, A. M. Asce, and K. Kim, "BIM-based decision-making framework for scaffolding planning," *Journal of Management in Engineering*, vol. 34, no. 6, article 04018046, 2018.

[47] Q. T. Le, A. Pedro, C. R. Lim, H. T. Park, C. S. Park, and H. K. Kim, "A framework for using mobile based virtual reality and augmented reality for experiential construction safety education," *International Journal of Engineering Education*, vol. 31, no. 3, pp. 713–725, 2015.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 3951986, 11 pages
https://doi.org/10.1155/2019/3951986

Research Article

Leveraging Mobile Augmented Reality Devices for Enabling Specific Human Behaviors in Design and Constructability Review

Suleiman Alsafouri [1] and Steven K. Ayer [2]

[1] *Project Manager, Corbins Electric, Phoenix, AZ, USA*
[2] *Assistant Professor, School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA*

Correspondence should be addressed to Suleiman Alsafouri; suleimanalsafouri@outlook.com

Received 29 November 2018; Revised 31 January 2019; Accepted 19 February 2019; Published 1 April 2019

Academic Editor: Mohammad R. Hosseini

Augmented reality (AR) may support effective design and constructability reviews by providing both the physical exploration benefits of traditional physical mock-ups and also the flexibility benefits of building information models (BIM). Many different types of mobile computing devices can present the same technical AR environment, but it remains unclear how the different properties of the devices impact user behaviors in an architecture, engineering, and construction (AEC) context. This study tasked users with completing the same design review task, using the same technical AR environment but viewed through different commercially available mobile AR devices. Specifically, 32 participants were tasked with collaboratively laying out and reviewing a simple office design using the randomly assigned AR device. Results showed 11 different behaviors were observed and different mobile computers elicited different behaviors. To add further context to the findings, the results were compared to those of a similar, previously published study where users completed a design review with the option to choose one or multiple AR devices. For several types of behaviors, including alternative design formation, navigation of design, and problem solving, no differences were observed between either groups or based on specific AR devices. Conversely, for other behaviors, including explanative, decision making, and discussions with team members, participants did not engage in these behaviors when they could self-select devices, but these behaviors were observed when participants were forced to use a particular device. This suggests that, for some applications, while users may tend to prefer one type of AR interface, they are fully capable of performing the same types of design review tasks with any AR device. The novelty of this work is in demonstrating how the context in which devices are applied impacts the ways in which they are used. This may help future practitioners and researchers to strategically choose to use, or not to use, certain types of devices to elicit specific behaviors.

1. Introduction

In recent years, many researchers have attempted to develop methods to resolve communication and coordination challenges related to using traditional two-dimensional documentation. With the increase of project complexity, traditional 2D documentation may not be adequate to represent all project information for project parties [1]. For example, observations of project meetings reveal that communicating project information through 2D representations limits project stakeholders' ability to work together to solve problems and make decisions [2]. In response to this recognition of limitations related to traditional 2D communication, researchers have explored various 3D visualization strategies, including virtual reality (VR) or building information modeling (BIM) walkthroughs, physical mock-ups, and augmented reality (AR).

The research community has gravitated toward using 3D visualization media in part because of recent developments in computing, modeling, and visualization technologies, which have become inexpensive and powerful. These technologies can facilitate collective decision making throughout project phases in the architecture, engineering, and construction (AEC) industries [2, 3]. This is especially important during design and constructability review sessions, when a number of project teams come together to review a design concept [3].

A prior study has explored how AR can enable different human behaviors in design review sessions by allowing participants to choose from various different mobile computers that are capable of displaying the same technical AR experience [4]. This prior work used the DEEPAND coding system developed by Garcia et al. [5] to identify 10 different behaviors that can impact the outcomes of the meeting using mobile AR computing tools [4]. In this prior study, participants were presented with a variety of mobile AR devices and those participants could freely choose to use any device at any point in the design review session. While the prior work enabled individuals to experiment with different devices to support AR visualization, it also provided an opportunity for participants to gravitate toward using devices for reasons other than pure effectiveness. In other words, it is possible that participants were more familiar with a particular computing device or had some other reason for using a particular device, which might have made them use it more. This could potentially increase their likeliness of demonstrating certain design review behaviors. While this approach provided evidence to illustrate the types of behaviors that AR may enable, it did not specifically illustrate the types of behaviors that might be observable in the presence of only a single device. In practice, many design review teams do not have a variety of devices to use for viewing the same environment. Therefore, this study aims to explore the extent to which the same behaviors observed in the prior study are also observable when the participants do not have the option to choose different devices. This may support technology planning in future studies to allow individuals to strategically plan for certain technologies to enable targeted human behaviors.

This study presents findings to address the following research questions:

(1) What human behaviors are observed with different mobile AR devices when participants are forced to use a particular device?

(2) How do the behaviors observed in this work compare and contrast to those observed during sessions where individuals were provided with various AR device choices?

To address these research questions, the authors conducted design review sessions with graduate and undergraduate students at Arizona State University. While it might initially seem like a limitation to study student participants with less experience than typical industry practitioners, it is common for owners without prior design review experience to be involved in these types of review sessions. In many cases, owners may have a strong understanding of their own needs but do not necessarily understand all detailed design or construction needs. Therefore, the authors aimed to replicate this type of scenario by creating a design review task that would require consideration of space constraints but would not require substantial prior industry experience to make plausible decisions. Furthermore, this approach of using student participants enabled the researchers to systematically test individual AR computing devices in a collaborative design review session, including devices that the prior study [4] suggested would be counterproductive for design review sessions. Therefore, the students were only provided with a single mobile computing device for experiencing the AR design environment. A structured analysis approach was used according to the coding strategies defined in DEEPAND [5] and the initial study [4]. The results are presented, and a detailed discussion is provided to provide insights into the similarities and differences that were observed between implementations.

2. Background

Design and constructability review sessions involve coordinating design information among project teams to understand and negotiate the interests and the objectives of the owners and the project in a timely manner [6–8]. This process focuses primarily on analyzing design components and methods such as structural, mechanical, electrical, and plumbing elements. In many cases, project stakeholders spend too much time and put too much effort trying to illustrate, define, and understand cross-disciplinary knowledge and information throughout design phases [9, 10]. As a result, important information is unable to be properly leveraged and decisions cannot be made efficiently [2, 11, 12]. However, with so many design and construction concerns to be discussed, analyzed, and decided upon, 3D visualization technologies have become increasingly useful and necessary.

Studies reveal that design review is crucial for identifying conflicts, errors, and inconsistencies in designs when using 3D representations, such as physical mock-ups and VR [6, 13]. Physical mock-ups and VR can support reviewers in addressing potential concerns prior to construction, such as constructability and assembly needs, safety, structural performance, environmental performance, and planning [14–16]. While several studies used physical mock-ups and VR to facilitate design review practices, AR has been also used in various collaborative tasks [14, 17, 18]. For example, AR has been used as an interactive architectural visualization tool [2, 19, 20] and also for evaluating heights of virtual buildings for site planning [21].

Researchers have also explored various different types of computing devices to display AR content. For example, smartphone-based AR has also been used for enhancing face to face collaboration and communication [22–25]. Personal computers have been used to model, simulate, and visualize AR construction scenarios [26]. A helmet-based wearable mobile computer was also developed and tested for on-site visualization of construction drawings and relevant information through a projection-based AR system [27, 28]. Moreover, Kopsida and Brilakis [29] provided a survey of different markerless solutions for pose estimation with respect to a known 3D model on mobile devices with 2D images, with a monocular algorithm for simultaneous location and mapping or with a combination of RGB images and the corresponding depth images [30]. They claim that the corresponding depth images solution should be the most robust solution to advance AR on mobile devices. These prior studies aimed to develop an AR environment for a single device in order to support a specific AEC use-case.

In most cases, the contributions of these prior works relate to proving that AR can support the targeted use-cases in some way. However, there is a limited understanding of how different mobile AR interfaces may enable different user behaviors when users have no choice to select a preferred AR device in design review sessions. Understanding the types of behaviors can support decision making when planning for the use of AR technology through specific computing interfaces to support specific human behaviors. This study aims to contribute to this understanding.

3. Methodology

Student participants were solicited for this study to complete design and constructability review sessions for a hypothetical office space using specific AR devices. These participants were video and audio recorded, and their behaviors were coded in order for the researchers to understand the typical types of behaviors demonstrated by individuals using different AR devices. Using students as participants allowed the researchers to repeat the same design review session, but to modify the specific AR device supplied to participants for completing the session. Furthermore, it allowed the researchers to incorporate AR devices that prior AR research [4] suggested should be counterproductive. This helped to identify the types of behaviors that would be observed by participants who were required to use a specific AR device for the entirety of their review session and did not have the option to choose to use different or additional devices.

3.1. Design and Constructability Review Scenario. The constraints of the hypothetical design scenario were the same for all participants. During each session, each of the two participants was provided with a single AR computing device. During different sessions, different pairs of participants were provided with different devices to allow each device to be tried in multiple sessions. The following sections present the detailed method involved in collecting and analyzing the data recorded from these sessions.

Upon arriving to the sessions, participants were given a quick introduction to AR and how they can use the device that they were both assigned. Then, they were presented with the design review activity. The participants were brought to a mostly empty room and told that they would need to plan for the layout of that space in order for it to serve as an executive office. This required them to plan out how they would want to arrange AR-based design components in the space. This scenario does not require substantial prior expertise to define a preferred layout as the students are familiar with the types of design components included (i.e., desks, cabinets, chairs, table lamps, and computers) and the general needs of an office worker. However, the activity did challenge students to collaboratively determine what elements they would include in their office layout, given the space constraints. Participants were provided with printed fiducial markers that represented various design elements. To ensure that participants would have to prioritize what objects would fit in their layout, they were intentionally given more office components to select than could realistically fit in the space. Figure 1 shows participants laying out these markers and determining how to best allocate space for the office layout according to the following design programming requirements:

(i) Required items needed to be added:

  (a) Office desk, office chairs, computer, table lamp, bookshelves, and office drawers.

(ii) Optional additional components:

  (a) Larger office desk options, office chairs (different styles and sizes), and other miscellaneous furniture options. These items challenged participants to find space in the office, which could not come at the expense of omitting required components.

(iii) Room constraints:

  (a) The size of the office (the physical room where the activity was conducted) could not be changed.
  (b) The built-in architectural elements in the space (including a window, door, electrical outlets, TV, and a built-in bookshelf) could not be changed.

The constraints provided a challenge to the student participants, but they also provided a direct method for allowing participants to engage with both physical and virtual objects involved in the session. In order to test different design concepts, participants were required to physically pick up and move printed fiducial markers. This behavior is simple to perform by participants, but it also enables the researchers to accurately code their behaviors (i.e., when a participant moves a marker, it is immediately clear that this represents the consideration of a design alternative). Therefore, this approach enabled the researchers to effectively observe how it might affect the behaviors of the participants.

Participants were allowed to lay out the space for as long as they felt was necessary, but most groups used approximately 30 minutes. When the participants felt that they had identified their ideal space layout, they were asked to document their design decisions on a form provided. This form tasked students with listing all items that they had selected, including both required and available options.

3.2. Technology Selection and Development. The mobile computing interfaces used in this study are listed in Table 1. These devices included both handheld and also wearable, head-mounted display- (HMD-) based devices. Both handheld and wearable devices represented a range of sizes and modes of displaying content, but all were chosen because they can present the same technical AR experience. Theoretically, the authors could have included other AR devices that involve newer, gesture-based, interaction

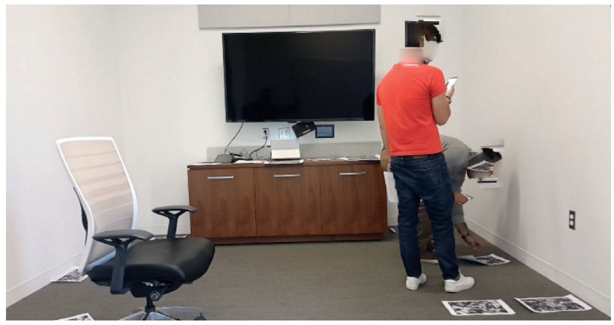


Figure 1: Interacting with printed fiducial markers that represented various design elements.

Table 1: List of devices interface used in this research.

Device type	Selected device
Small smartphone screen size	3.8″ smartphone: Samsung Galaxy T599
Large smartphone screen size	5.7″ smartphone: Samsung Galaxy Note 5
Small tablet screen size	9.7″ phablet: Samsung Galaxy Tab S2
Large tablet screen size	12.2″ tablet: Samsung Galaxy Tab Pro
One eye screen smart glass	Vuzix Smart Glass M100
Dual eyes screen glasses	VR box (note: while this device has "VR" in the title, video pass-through AR was used for data collection)
Duel eyes transparent smart glasses	Epson smart glasses: BT-200
Tablet mounted on a stand	12.2″ tablet: Samsung Galaxy Tab Pro

(i.e., Microsoft HoloLens), but this change in interaction could also have an impact on the users' ability to interact with the AR content. Therefore, these devices were selected because they allowed for exactly the same type of marker-based AR interaction.

The authors followed a structured process to develop a single AR application that could be built to all of the devices that were used in the design and constructability review sessions [31]. Using an Android-based, mobile AR application that allows users to visualize virtual objects in a physical space, participants were given various printed fiducial markers that represented different design elements. Regardless of the device they were given, the interaction with AR involved participants placing markers on the ground, pointing the computing device camera at the markers, and viewing augmented content at full scale. This allowed participants to physically navigate around the space, and their view of the "augmented" content would modify accordingly. This development approach also enabled the researchers to have a consistent AR environment for comparison between all devices.

4. Data Collection and Analysis

The research techniques adopted in this study aimed to facilitate comprehensive data collection. The authors used direct observation to record behaviors as they occurred. These observational data were collected through video and audio recordings of the sessions. Previous research has categorized the behaviors people exhibit when working together in engineering meetings [2, 5]. This prior work classified meeting activities by analyzing the ways people interacted, participated, and contributed to meetings, as well as the way projects evolved. They classified all utterances spoken during several engineering meetings according to the reactions they promoted. They also identified seven codes of behavior among participants that influenced the outcomes and efficiency of the meetings, including describe; explain; evaluate; predict; formulate alternative; negotiate; and decide (DEEPAND). In this research, the authors have used the codes of behavior from DEEPAND as their coding system to study participant behaviors. The authors also developed five additional codes of behavior that could occur in an AR environment that were not included in the original DEEPAND system. All codes used from DEEPAND and those developed specifically for AR are shown in Table 2. Furthermore, the definitions of these behaviors and examples that were observed in this study are provided to clarify how the data were analyzed in this research.

The authors analyzed the data in each category as either a time- or event-based dataset. The time dataset records the amount of time spent engaging in a given behavior while using a different mobile computer. In this category, eight codes of behaviors were considered, including visualizing; describing; explaining; evaluating; predicting; walking/navigating through a design; discussing while looking at others; and discussing while looking at the markers. The time spent on each behavior was noted in intervals of minutes. The events dataset counted the number of occurrences of different behaviors. Three codes were considered for this dataset, including deciding; problem solving; and formulating alternatives (moving markers). This approach of coding certain behaviors based on the total time and others based on the number of occurrences was implemented to try

Table 2: Definitions and examples of all behaviors used in this study.

Code of behavior	Definition	Example	Definition reference
Describe	Show or display what is explicit. What, where, when, who information	"We have one office desk and three chairs, we can start with the office desk as this would be the largest item in the design"	[5]
Explain	Think aloud. Why, why not information	"We should use a smaller office desk and place it in the corner away from where the office door swings inward"	[5]
Evaluate	Assess extent to which a design option meets the needs. What is better? Does it meet requirements?	"This chair does not match the desk design, we need to go with a different design... at least matching the colors"	[5]
Predict	What if scenarios	"There may be no enough space for people to sit if we use this desk and those chairs. We will get more room for people if we move the desk to that corner and move the chairs accordingly."	[5]
Formulate alternative (move markers)	Create new design alternatives	When replace, relocate, or change markers' orientation	[5]
Negotiate	Negotiate tasks and responsibilities	Define who will detail a specific alternative solution "[a request to the other participant] move this marker to this side and we will be done here"	[5]
Decide	Select design option	"Is this a good location? [they refer to the book shelve]" "Yes that is perfect"	[5]
Discuss while looking at others	When having face-to-face communication	Any comments or verbal related to the design but participants having face-to-face communication "do we really need a foosball in the office? I do not think this is achievable in this room"	[4]
Discuss while looking at the markers	When communicating with others while looking at the design	Any comments or verbal related to the design but participants navigate through the design "moving the bookshelves to here (the other side of the wall) may give better space in this area (the center of the room)"	[4]
Problem-solve	Decision-making event "agreement" occurred after defining design problem	"The computer is merged with the desk, we need to move it up or down." The action has been taken to solve the conflict	[4]
Visualize	When holding/wearing a device, looking through the device's screen, and visualizing (including seeing or not seeing virtual objects)	Holding or wearing a device, looking through the device's screen	[4]
Walk/navigate through a design	When holding/wearing a device and walking to navigate the design pieces	Holding or wearing a device and walking around virtual objects	[4]

to provide meaningful results based on how teams might actually want to use the findings of this work. For example, "formulate alternative (move markers)" could theoretically be treated as a time dataset, but the time it would take to move markers would be highly dependent on factors outside of the AR device used (i.e., if the size of the room were much larger, it may take longer to move markers per alternative, but this still indicates the same number of considerations of design alternatives). Therefore, the researchers aimed to use coding approaches that would provide practical meaning to the data collected.

The observed time for each behavior was normalized to provide an average use per person. Because some sessions took longer than others, the results were divided by the total time spent in each session to indicate the average time spent for a specific behavior per minute. For example, when using handheld devices with less than a four-inch screen, 4 participants spent 24 minutes visualizing and they took 50 minutes to complete the 3 sessions. Therefore, the average use per person was calculated according to the following equation:

$$\frac{24\,(\text{minute})}{4\,(\text{persons})} = 6 \text{ minutes of visualizing behavior per person.} \quad (1)$$

After determining the average use per person, the average use per minute was calculated according to the following equation:

$$\frac{6\,(\text{minutes visualizing per person})}{50\,(\text{total sessions time})} = 0.12 = 12\%\,(\text{percentage in visualization time per person per minute}). \quad (2)$$

The main purpose of this analysis strategy is to normalize the data so that the observed behavior that occurs per minute can be seen without considering the variance of the total time of the sessions. All observational data were normalized based on the total amount of time that participants spent in the session. The following sections use these percentages to report results.

5. Results and Discussion

In total, 32 participants completed AR-based design and constructability reviews for this research in 16 design and constructability review sessions, with two participants per session. In each review, a different AR device was provided, but the same device was given to both participants involved in the specific session. In total, eight devices were tested throughout all sessions, which meant that each device was tested by four participants in two sessions. In every session completed by every participant, the office space layout design and constructability use-case and AR experience created remained identical. The results from the data collected were sorted in Table 3 to illustrate the percentage of each behavior observed in this research.

In order to provide meaningful results, the discussion sections are separated by the specific behaviors coded. The results observed through the different AR-based design review sessions are included. Additionally, results from prior, industry-based AR design review sessions [4] are provided in order to add context to the results based on whether or not participants could choose their own AR device. This is especially important for this work because this comparison helps to provide evidence of the types of behaviors commonly exhibited among participants when they do and do not have the option to choose different devices.

5.1. Descriptive. Descriptive behaviors were identified as those when participants simply stated what something was in the AR space. For example, participants would often describe what they were looking at as a preface to a subsequent evaluative behavior. Descriptive behavior was coded as a time-based behavior to allow researchers to understand the extent to which people are engaged in this behavior during the design review sessions.

This behavior was observed in this student-based work with all devices that were tested. Similarly, it was also observed in the prior industry-based work using all devices tested. Based on the data collected, there is no evidence to suggest a major difference in descriptive behaviors among users in either study using any devices.

Admittedly, both sessions indicated that users described their environment the least when using a single-eye see-through AR glass. While this might initially suggest that head mounted displays (HMDs) do not support descriptive discussion among participants as much as handheld devices, other HMDs observed elicited comparable amounts of descriptive behavior as compared to the handheld devices. Therefore, it may be more likely that the single-eye see-through AR glass, specifically, was not as well suited to this behavior.

5.2. Explanative. Unlike descriptive behavior that simply aims to describe the "who," "what," "when," and "where" information related to a situation, explanative behaviors are identified when participants explain *why* something is the case. For example, users might explore the AR environment and explain why they placed the office desk in the corner away from where the office door swings inward. Explanative behavior was coded as a time-based behavior, which allowed researchers to understand the extent to which it occurred.

This behavior was observed in all sessions with student participants using all devices. However, it was not observed in the prior industry-based study when participants used handheld screens less than 4″; two-eyed see-through glasses; or one-eyed see-through glasses. This suggests that participants would likely prefer not to use these types of devices when explaining an attribute of a design. This preference to use devices with a larger or more intuitive display may seem largely expected. What is more noteworthy about this comparison is the observation that when not provided with an option to use a more preferable device, users will still be able to explain their thoughts about a particular situation using any of the AR devices tested.

5.3. Evaluative. Evaluative behaviors are those that include an assessment of the extent to which a certain design element will meet the needs of the team. For example, participants might state that a certain desk placement did not provide adequate room for them to swivel in their office chair, which would not be conducive to working in the space. This type of behavior was coded as a time-based behavior as there are not clear delineations between evaluative comments within a single statement or series of statements by participants.

This behavior was observed in all student-based sessions with all devices tested. It was not observed in the prior study when participants used small handheld mobile devices less than 4″; one-eyed see-through AR glasses; or two-eyed see-through glasses. Similar to the explanative behaviors, this suggests that when participants are forced to use a certain AR device, they will be able to evaluate a design. However, unlike the descriptive findings, evaluation may indicate a more cognitively challenging task that requires more consideration from users. It is worth noting that in both student-based and industry-based sessions, there appear to be substantial differences in the extent to which participants demonstrate evaluation in AR. Tablet-based devices consistently led to higher amounts of evaluation among participants. Conversely, HMDs seemed to consistently elicit less (or no) evaluation among participants. This suggests that not only do participants seem to avoid using HMDs for

Table 3: AR interfaces and behaviors observed in the study.

Observed Behavior	Device interface							
	Handheld with screen less than 4 inches	Handheld between 4 and 6 inches	Handheld between 6 inches and 10 inches	Handheld larger than 10 inches	Two-eyed see-through glasses	One-eyed see-through glasses	Video see-through VR box	Tablet mounted on a stand
				Time data				
Visualizing	12.3%	11.9%	14.2%	12.0%	6.2%	15.5%	15.1%	12.8%
Descriptive	17.3%	12.8%	17.1%	3.8%	0.7%	12.6%	18.7%	16.9%
Explanative	19.1%	12.9%	16.7%	8.0%	2.3%	13.0%	5.9%	22.2%
Evaluative	8.2%	20.5%	17.9%	3.0%	0.8%	4.5%	3.4%	41.7%
Predict	25.5%	12.9%	23.1%	13.8%	0.0%	14.6%	4.3%	5.8%
Negotiate	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Walking/navigating through design	12.9%	10.1%	13.6%	2.7%	5.9%	23.0%	16.6%	15.2%
Discussing about the design while looking to each other (face-to-face communication)	15.1%	18.5%	14.2%	1.7%	4.2%	16.4%	14.0%	16.0%
Discussing about the design while looking to markers	12.5%	21.0%	25.8%	1.2%	5.0%	11.8%	12.9%	9.9%
Total time/device (minutes)	**20.2**	**18.7**	**15.9**	**23.0**	**17.7**	**16.2**	**12.3**	**28.8**
				Event data				
Decision making	18.3%	15.6%	20.2%	23.3%	1.5%	7.3%	5.7%	8.0%
Problem solving	16.8%	17.9%	16.2%	21.2%	2.2%	7.8%	8.9%	8.9%
Design changes (alternatives)	14.9%	15.7%	13.2%	13.3%	11.8%	6.8%	10.0%	14.2%

design evaluation, but even if they are not given an option on device, they do not evaluate attributes of the design as often.

5.4. Predictive. Predictive behavior occurs when participants discuss what they believe would be potential impacts of a particular design change. For example, they might discuss cost implications of using a larger office desk option in their space and how that could potentially impact the effectiveness of a given layout. Similar to the prior behavior codes, predictive behavior was coded as a time-based behavior as there often was not a clear end point or number of predictions made within a particular statement of a participant.

This behavior was observed in all student-based implementations with all devices except two-eyed see-through glasses. Conversely, it was not observed in any of the discussion among the industry members. This may imply that the industry participants felt that certain impacts of decision changes were obvious because of the experience that all participants had, but it could also be due to the slight differences in the design activities that were compared. For example, in the student-based activity, participants had to fit all design content within the confines of a single, existing space. In the industry-based study, the team was not given specific room constraints to their design challenge. Therefore, the researchers do not conclude that certain devices are likely to enable or inhibit specific predictive behaviors among participants.

5.5. Alternative Design Formulations. While predictive behaviors describe the impact envisioned from a potential design change, alternative design formulation behaviors simply explore different designs for a space. Because this study leveraged marker-based AR, this was coded as an event data point. Anytime a participant moved a printed fiducial marker in their space, this was coded as an alternate design that they explored. For example, when experimenting with placement of the required office desk, participants may move the printed fiducial marker several times to explore different layout options. Each movement was counted as an alternative design formulation.

This behavior was observed in all student-based implementations using all AR devices tested. It was not observed when using every device in the industry-based study. Specifically, the prior work did not observe this behavior when using the VR box or the smallest smartphone less than 4″. The design activity incorporated in both the student- and industry-based events required participants to lay out a particular space within certain constraints. In all cases, participants were initially given a stack of printed markers that were not placed anywhere. This forced them to determine an initial design on their own. While this method allows participants to demonstrate evolution in their design considerations, it almost guarantees that they will demonstrate this behavior of design alternative formulation. The only exceptions that were observed were in the collaborative industry-based session where users could choose their own device. For example, if a user was wearing the VR box, which presented video pass-through-based AR, and wanted to explore a different design, they would occasionally mention to another participant to move a marker to explore a different option. Therefore, while they did not technically display this behavior in all sessions, it seems reasonable to claim that it is likely that all devices tested would support either direct formulation of alternatives or at least considerations related to design alternatives.

5.6. Negotiating. Negotiating behaviors relate to discussion about who will handle certain responsibilities based on an outcome of the design review session. For example, if a participant were to ask or instruct another to complete a cost estimate or model change based on a decision made during the design review, this could constitute a negotiation activity. This behavior was not observed in either the student-based or industry-based study. This is likely a result of the implementation strategy. During both implementations, participants were asked to complete a single design review of a space and were not asked to complete a follow-up review or complete design tasks after the event. It is likely that negotiating behaviors would have been observed if this mode of visualization were tested on an actual project where stakeholders would be required to plan around the outcomes of the design review meeting, but the authors of this study cannot make claims about this behavior based on the data collection approach used.

5.7. Decision Making. Decision-making behaviors are considered to be those where participants come to an agreement about a particular design element. For coding this type of behavior, the authors identified instances when a participant proposed a design alterative and when another confirmed that the alternative would meet the needs of the project. Because these behaviors have a clear proposition of a design concept and acceptance from another participant, they were coded as event-based data.

In the student-based study, decisions were made by participants using all devices. For the industry-based study, decisions were not made with either the handheld tablet or tablet mounted on a stand, nor were they made with small handheld devices less than 4″. This suggests that all devices may facilitate decision making to some extent if participants are not given a choice about what device they use.

5.8. Navigating the Design. Navigation behavior was coded specifically for AR-based design reviews. For traditional design review sessions that might involve traditional plans and architectural renderings, it is difficult or impossible to know the extent to which participants navigate a design. However, in AR, users physically explore the space to see the design from different perspectives. Therefore, this behavior was coded as a time-based behavior to determine which devices elicited the greatest and least amount of physical exploration through a space.

This behavior was observed in all student-based sessions with all AR devices tested. It was also observed in all industry-based sessions using all devices provided. This seems to indicate a fundamental performance attribute of AR: it enables physical exploration of a space. While this may not always be beneficial in all situations, the building industry is unique from other industries in that many times the final built product cannot be developed through iterative testing. Instead buildings must be completed correctly the first time they are made. Therefore, the ability of AR to support physical exploration of a space seems to provide potential advantages for project stakeholders to explore building design concepts.

5.9. Discussing the Design with Others. This behavior included any of the verbal behaviors mentioned earlier that involve more than one participant. In other words, if a participant was thinking aloud to him or herself, this was not considered to be discussion with other participants, but anytime a statement was made to inform or engage with another participant, this was considered as time spent discussing with others. To further understand how the different devices support engagement with the model or engagement with other participants, this coding category was separated into time spent discussing the design when looking at other participants and time spent discussing the design when looking at the design.

This behavior was observed in all student-based implementation sessions with all devices tested. However in the prior study, this was only observed when using tablet-based devices (either handheld or mounted on a stand). This initially seems to suggest that head-mounted displays might be less conducive to supporting discussion among participants. However, when looking at the student data, there is clear evidence of discussion occurring between student participants and also when students are looking at the model content in AR. This seems to indicate that while participants may not always prefer HMD-based devices for discussing a design, these can lead to different modes of group discussion in the absence of device choice.

5.10. Problem Solving. Problem solving was defined in this work as any event where a decision was made as previously coded that specifically followed the identification of a problem related to a design. This was collected to try to identify the decisions that may have required more cognitive effort from participants. In other words, in both design activities, there may be certain design attributes that may not require substantial consideration from the participants. By considering decisions that were made after a problem was identified, this helps to illustrate the specific cases of decisions that were made that required actual consideration of the needs of the design task to generate agreement about a design approach. Similar to the coding approach used for decision making, this event has a clear start point (proposing a design alternative) and end point (acceptance of proposition). Therefore, these were categorized as event data.

This behavior was observed in all student-based sessions using all devices tested. It was not observed with most of the devices in the industry-based session. It is possible that this is because the initial design alternatives explored by the industry participants were guided by their prior experience and therefore less likely to lead to problematic issues that would require a subsequent problem-solving decision. It is also possible that this had to do with the design challenge given to the different groups that may have been more or less likely to lead to problems that would need to be addressed. Because all student groups using all devices still indicated problem-solving behaviors, the authors conclude that all devices could support this type of behavior among participants.

6. Noteworthy Trends in Findings

The findings from this study indicate a few trends when exploring them in conjunction with one another. First, the study demonstrates that while there are often preferences of users to leverage certain technologies more than others, this often does not mean that the device specifically enables or inhibits certain behaviors. For example, when looking at explanation, evaluation, alternative design formation, decision making, and discussion among the team members, these behaviors were frequently not observed with certain devices in the industry-based design review session, but they were often observed in the student-based sessions. This demonstrates that while users may have a preference to a certain type of device, they may still be able to engage in a certain behavior if they do not have the choice to select a more preferable device.

Similar to the time-based data, it is worth noting the similarities between high-occurrence events that were observed through larger tablets and the comparatively low-occurrence events that were observed on the head-mounted displays. This is noteworthy because a head-mounted display-based AR environment might initially seem to offer advantages for marker-based AR because it frees the users' hands for moving markers and exploring designs. Based on the findings of this work, this assumption does not always seem to be the case. It is possible that this indicates that head-mounted AR does not support these behaviors as much as handheld, but it could also be related to the fact that the devices used a video pass-through method for realizing AR. This would offer an opportunity for a future study to explore the extent to which these behaviors are observable using a newer head-mounted AR device that does not use a video pass-through system (for example: Microsoft HoloLens).

Another noteworthy finding between the prior study and this one relates to the behaviors exhibited while using the handheld mobile computing devices. In the prior study, few if any design alternatives were explored when using smartphone-sized devices. Conversely, in this study, design alternatives appear to be explored at approximately the same rate between all handheld devices. This seems to indicate that while users may prefer to view AR on larger tablets or "phablets," in the absence of choice, all handheld devices seemed to elicit similar levels of exploration of design alternatives. This is especially important for design and constructability review sessions. One of the core functions of these review sessions is to enable team members to identify potential issues with a concept and explore potential alternatives. The comparison of these findings suggests that while users may gravitate toward using larger devices for exploring design alternatives, similar frequencies of this behavior may be observed through the use of smaller handheld devices as well.

7. Research Limitation

The authors of this study intentionally developed the exact same technical AR experience for all devices tested. While the same environment was built to each device, different computing devices had some differences in terms of technological hardware. This means that some devices may run the application more smoothly than others. The authors were interested in understanding the behaviors elicited or inhibited using the different technologies, so any hardware limitations that may have influenced user behavior in this study would still be relevant for future researchers who use a similar type of hardware. However, as technologies continue to evolve, it is likely that new devices would enable interactions with the AR environment in a fundamentally different way than those tested in this study. For example, new and emerging holographic AR displays (i.e., Microsoft HoloLens or Magic Leap) do not generally rely on marker-based approaches to content tracking and may provide different capabilities than the HMDs tested in this research. As a result, the authors elected to focus on testing different technologies that could all run the same technical marker-based AR environment, but they do not make claims about emerging technologies that function in fundamentally different ways than those tested.

8. Conclusion

This study aimed to understand how different mobile computing technologies presenting the same technical AR environment may enable or hinder different user behaviors in a design review context, based on whether or not users had a choice to select a preferred AR device. By comparing two groups of participants with and without the ability to choose AR devices, the authors were able to identify several noteworthy trends about how different devices enabled or inhibited behaviors.

In some cases, there appeared to be differences in behaviors enabled through different types of AR devices, regardless of whether participants could choose their device or not. For example, regardless of choice, HMDs did not generally elicit evaluative behaviors. Typically, these types of behaviors involve input from various team members. Gaining input from a team member while wearing a HMD would involve a user observing his or her team members through the device. In the marker-based HMDs tested, this means that participants would see their team members through a video screen. It is possible that this type of interaction influenced users while evaluating the design with the HMDs. It is also possible that emerging HMDs that are moving away from video pass-through AR may also be able to better support evaluative behaviors.

For other behaviors studied, all AR devices seemed to elicit certain behaviors, whether or not users had the choice to select their own device. For example, in both studies, users engaged in alternative design formulation; navigation of design; and problem solving. These findings largely aligned with researcher expectations. Creating a marker-based application is likely to encourage alternative design formulation regardless of the device chosen, and the task of agreeing on a design concept among a team of individuals is likely to require problem solving. Furthermore, physical navigation of the design is one of the core benefits afforded by AR, as compared to reviewing a static document or virtual model. Therefore, while partially intuitive, these findings indicate core affordances that all AR devices seem to enable, regardless of whether users may select their own device.

Perhaps the most noteworthy conclusions of this work relate to the observations that differed between groups based on whether or not participants had a choice in selecting their AR device to use. For several behaviors on certain devices, participants who had a choice to select certain devices did not exhibit certain behaviors. However, when not provided with a choice, the same behaviors were exhibited on all devices. These behaviors included explanative; decision making; and discussing with others. These findings are noteworthy because researchers and practitioners who conduct design review sessions with a new visualization technology, such as AR, are unlikely to provide multiple devices that deliver the same technical experience. Instead, they are more likely to own or purchase a particular type of device that they would implement for the session. The novelty of this work is in providing evidence that for certain behaviors, exact AR device types may not matter for supporting specific behaviors. This may help to guide researchers and practitioners when planning for what computing devices to purchase for AR design review sessions, based on what may offer the most range of effective uses for their needs.

Data Availability

The authors of this work will share aggregated results from this research but cannot release individual data points from human subjects, in accordance with their institutional review board's requirements. Furthermore, the authors will also share models that were used for the AR design review sessions described in this work. This will allow other researchers to replicate the activity if it is of interest. If a reader would like to access any available data, please contact the authors directly with their request for information.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank all the participants who agreed to complete the AR design review activities that made this research possible. This material is based upon the work supported by the National Science Foundation under grant no. IIS-1566274.

References

[1] K. Liston, M. Fischer, and T. Winograd, "Focused sharing of information for multidisciplinary decision making by project teams," *ITcon*, vol. 6, pp. 69–82, 2001, http://www.itcon.org/2001/6.

[2] J. Du, Z. Zou, Y. Shi, and D. Zhao, "Zero latency: real-time synchronization of BIM data in virtual reality for collaborative decision-making," *Automation in Construction*, vol. 85, pp. 51–64, 2018.

[3] D. Paes, E. Arantes, and J. Irizarry, "Immersive environment for improving the understanding of architectural 3D models: comparing user spatial perception between immersive and traditional virtual reality systems," *Automation in Construction*, vol. 84, pp. 292–303, 2017.

[4] S. Alsafouri, "Information technology and human factors to enhance design and constructability review processes in construction," Doctoral dissertation, Arizona State University, Tempe, AZ, USA, 2017.

[5] A. C. B. Garcia, J. Kunz, and M. Fischer, "Meeting details: methods to instrument meetings and use agenda voting to make them more effective," CIFE Report No. TR147, Stanford University, Stanford, CA, USA, 2003, https://cife.stanford.edu/sites/default/files/TR147.pdf.

[6] E. W. East, J. G. Kirby, and G. Perez, "Improved design review through web collaboration," *Journal of Management in Engineering*, vol. 20, no. 2, pp. 51–55, 2004.

[7] S. Mehrbod, S. Staub-French, N. Mahyar, and M. Tory, "Characterizing interactions with BIM tools and artifacts in building design coordination meetings," *Automation in Construction*, vol. 98, pp. 195–213, 2019.

[8] J. H. Park and G. Lee, "Design coordination strategies in a 2D and BIM mixed-project environment: social dynamics and productivity," *Building Research & Information*, vol. 45, no. 6, pp. 631–648, 2017.

[9] F. Leite, Y. Cho, A. H. Behzadan et al., "Visualization, information modeling, and simulation: grand challenges in the construction industry," *Journal of Computing in Civil Engineering*, vol. 30, no. 6, article 04016035, 2016.

[10] L. Soibelman, R. Sacks, B. Akinci, I. Dikmen, M. T. Birgonul, and M. Eybpoosh, "Preparing civil engineers for international collaboration in construction management," *Journal of Professional Issues in Engineering Education and Practice*, vol. 137, no. 3, pp. 141–150, 2011.

[11] S.-C. Kang, H.-L. Chi, and E. Miranda, "Three-dimensional simulation and visualization of crane assisted construction erection processes," *Journal of Computing in Civil Engineering*, vol. 23, no. 6, pp. 363–371, 2009.

[12] M. V. Sierra-Aparicio, J. L. Ponz-Tienda, and J. P. Romero-Cortés, "BIM coordination oriented to facility management," in *Advances in Informatics and Computing in Civil and Construction Engineering*, pp. 123–128, Springer, Cham, Switzerland, 2019.

[13] F. P. Rahimian and R. Ibrahim, "Impacts of VR 3D sketching on novice designers' spatial cognition in collaborative conceptual architectural design," *Design Studies*, vol. 32, no. 3, pp. 255–291, 2011.

[14] M. A. Froehlich and S. Azhar, "Investigating virtual reality headset applications in construction," in *Proceedings of the 52nd ASC International Conference*, Provo, UT, USA, April 2016, https://pdfs.semanticscholar.org/725d/24183d51bb14121e3a50e6022a0914cb9e95.pdf.

[15] R. Gopinath, "Immersive virtual facility prototyping for design and construction process visualization," Doctoral dissertation, Pennsylvania State University, State College, PA, USA, 2004.

[16] T. Majumdar, M. A. Fischer, and B. Schwegler, "Conceptual design review with a virtual reality mock-up model," in *Proceedings of Joint International Conference on Computing*

and Decision Making in Civil and Building Engineering, pp. 2902–2911, Montréal, Canada, June 2006.

[17] A. Hammad, H. Wang, and S. P. Mudur, "Distributed augmented reality for visualizing collaborative construction tasks," *Journal of Computing in Civil Engineering*, vol. 23, no. 6, pp. 418–427, 2009.

[18] F. Milella, *Problem-Solving by Immersive Virtual Reality: towards a More Efficient Product Emergence Process in Automotive*, STFC Daresbury Science and Innovation Campus, Warrington, UK, 2015, ISSN: 3159-0040, http://www.jmest.org/wp-content/uploads/JMESTN42350676.pdf.

[19] M. Rohani, M. Fan, and C. Yu, "Advanced visualization and simulation techniques for modern construction management," *Indoor and Built Environment*, vol. 23, no. 5, pp. 665–674, 2014.

[20] J. Wang, X. Wang, W. Shou, and B. Xu, "Integrating BIM and augmented reality for interactive architectural visualisation," *Construction Innovation*, vol. 14, no. 4, pp. 453–476, 2014.

[21] N. Yabuki, K. Miyashita, and T. Fukuda, "An invisible height evaluation system for building height regulation to preserve good landscapes using augmented reality," *Automation in Construction*, vol. 20, no. 3, pp. 228–235, 2011.

[22] M. Billinghurst, S. Weghorst, and T. Furness, "Shared space: an augmented reality approach for computer supported collaborative work," *Virtual Reality*, vol. 3, no. 1, pp. 25–36, 1998.

[23] A. Henrysson, M. Billinghurst, and M. Ollila, "Face to face collaborative AR on mobile phones," in *Proceedings of the 4th IEEE/ACM International Symposium on Mixed and Augmented Reality (ISMAR'05)*, pp. 80-89, IEEE Computer Society, Vienna, Austria, October 2005.

[24] T. Wang, H. Zhang, X. Xue, and S. Cai, "Augmented reality-based interactive simulation application in double-slit experiment," in *Online Engineering & Internet of Things*, pp. 701–707, Springer, Cham, Switzerland, 2018.

[25] X. Li, W. Yi, H.-L. Chi, X. Wang, and A. P. C. Chan, "A critical review of virtual and augmented reality (VR/AR) applications in construction safety," *Automation in Construction*, vol. 86, pp. 150–162, 2018.

[26] Y. Turkan, R. Radkowski, A. Karabulut-Ilgu, A. H. Behzadan, and A. Chen, "Mobile augmented reality for teaching structural analysis," *Advanced Engineering Informatics*, vol. 34, pp. 90–100, 2017.

[27] F. Dai and A. Olorunfemi, *Holographic Visual Interaction and Remote Collaboration in Construction Safety and Health*, West Virginia University, Morgantown, WV, USA, 2018, https://www.cpwr.com/sites/default/files/publications/SS2018-visual-interaction-remote-collaboration.pdf.

[28] K. C. Yeh, M. H. Tsai, and S. C. Kang, "On-site building information retrieval by using projection-based augmented reality," *Journal of Computing in Civil Engineering*, vol. 26, no. 3, pp. 342–355, 2012.

[29] M. Kopsida and I. Brilakis, "BIM registration methods for mobile augmented reality-based inspection," in *Proceedings of the European Conference on Product and Process Modelling*, pp. 1–7, Limassol, Cyprus, September 2016, http://www.see.eng.osaka-u.ac.jp/seeit/icccbe2016/Proceedings/Full_Papers/206-191.pdf.

[30] R. Mur-Artal, J. M. M. Montiel, and J. D. Tardos, "ORB-SLAM: a versatile and accurate monocular SLAM system," *IEEE Transactions on Robotics*, vol. 31, no. 5, pp. 1147–1163, 2015.

[31] S. Alsafouri and S. K. Ayer, "A step-by-step procedure for implementing mixed reality visualization interfaces in design and constructability review sessions," in *Proceeding of Lean and Computing in Construction Congress-Volume 1: Proceedings of the Joint Conference on Computing in Construction (JC3)*, pp. 913–921, Heraklion Greece, July 2017.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 3690419, 15 pages
https://doi.org/10.1155/2019/3690419

Research Article

Ontology-Based Representations of User Activity and Flexible Space Information: Towards an Automated Space-Use Analysis in Buildings

Xingbin Chen,[1] Tae Wan Kim,[2] Jiayu Chen ,[3] Bin Xue,[3] and WoonSeong Jeong [4]

[1]*Department of Engineering Management, School of Civil and Transportation Engineering, Guang Dong University of Technology, Guangzhou, Guangdong 510006, China*
[2]*Division of Architecture and Urban Design, Incheon National University, Incheon 22012, Republic of Korea*
[3]*Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong*
[4]*Department of Architectural Engineering, Chungbuk National University, Cheongju 28644, Republic of Korea*

Correspondence should be addressed to WoonSeong Jeong; wsjeong@chungbuk.ac.kr

Received 25 November 2018; Revised 28 January 2019; Accepted 18 February 2019; Published 1 April 2019

Academic Editor: Mohammad R. Hosseini

Space-use analysis offers quantitative and reliable references to support architects' decision-making regarding the planning and design of flexible spaces. To allow for automated space-use analyses of such flexible space, it is imperative to create activity and space ontologies that offer systematic and explicit forms representing user activities and the spaces in which they occur. Therefore, this study extends the current research on activity ontologies in order to capture flexible space-use patterns for user activities and develops a new space ontology by abstracting the information related to both flexible and nonflexible spaces. In addition, this study formalizes a framework for an automated space-use analysis implementation process that predicts and updates flexible space utilization by integrating user activity with flexible space. This work contributes to performance-based building design by providing a common, computer-interpretable vocabulary for representing user activities and flexible spaces and a framework for an automated space-use analysis implementation process that informs space utilization (i.e., a space efficiency measurement).

1. Introduction

In recent years, improving building space efficiency has become a primary concern in building design. It not only relates to economic considerations but also to a building's thermal load and energy consumption level, both of which are associated with a building's carbon footprint and overall level of sustainability. Therefore, it is critical for architects to predict space utilization during the planning phase with reliable measurements of space efficiency [1]. Architects prefer design options that use minimal space, while still satisfying the building's functionality and allowing for various occupant activities. Flexible space is a popular choice in space planning because it promotes space efficiency, due to the ease of reconfiguration made possible by movable components. Such spaces offer a greater net usable area and increased occupant density that contribute to a building's economy [2, 3]. However, conventional space utilization assessment methods such as workplace planning [4] and automated space-use analysis (SUA) [5] cannot yet deal with predicting the utilization of flexible space. In addition, the traditional evaluation methodology has not fully utilized integrated information models such as building information models (BIMs) to analyze space usability. As a result, architects must make such predictions on an ad hoc basis, which can be both time-consuming and inconsistent.

1.1. Motivating Cases. The Cygnaeus High School project in Finland [4] was required to reduce the school's net spatial area from 6,926 m^2 to 6,508 m^2, without losing any function or activities space. The planner pointed out that the auditorium (270 m^2 in area) was only used for educational purposes approximately 2% of the time. Because the activities it accommodated required a small time-load but large amount of space, it was suggested that the auditorium be removed and turned into three adjacent flexible classrooms (80 m^2 each). These flexible classrooms could then be combined into one large space by uniting the three subunits, but only for the activities previously supported by the auditorium. The Vodafone office in England [6] is a similar case. In order to improve space planning efficiency and create a multifunctional environment in a minimum amount of space, architects planned for two flexible meeting rooms that could be combined into a bigger space to support events with larger user groups. The Kentish Town Health Centre [6], a health clinic located in England, is the third example. Architects must closely engage with their customers if they are to plan spaces that meet the client's changing needs. In the beginning, the centre was planned with eight meeting rooms, based on the client's practical needs. As the flexible space offers a larger net usable area, five of these meeting rooms were designed to be flexible, with three subunits. However, after occupying the buildings, it was determined that some of these spaces were underutilized, which implies that manual SUA interpretation for flexible space can be error-prone. Therefore, the client required renovation so as to transform them into two counseling spaces [7, 8].

These examples illustrate that the current SUA is not yet tailored to accommodate flexible space. Architects must manually interpret on an ad hoc basis, due to the different types of flexible space-uses and activities, as well as the many properties of flexible space itself. Taking the Cygnaeus High School project as an example, if a teaching activity required a 160 m^2 classroom and the classroom was defined as a supertype space, given the current representations of activity and space, the spaces identified would be several nonflexible classrooms and one large flexible classroom (i.e., the 240 m^2 space created by combining the three subunits). Existing knowledge of SUA does not permit (1) an appropriate set of properties to be formulated for the spatial requirements of user activities, which could be applied to distinguish between flexible and nonflexible space-use or (2) a definition of a sufficient set of flexible space properties, since the properties of such a changeable space are not yet available.

1.2. Research Objectives and Scope. To fill this research gap and enable an automated SUA for flexible space, the objectives of this study are (1) to develop user activity and space ontologies that function as a common vocabulary and enable seamless performance of automated SUAs for both flexible and nonflexible space-use and (2) to extend the SUA framework [5] defining an automated SUA implementation process in flexible space, enabling architects to quickly and consistently predict its utilization based on activity and space information and update the prediction when changes occur. This will support architects' decision-making regarding their designs. The present study focuses primarily on office and institutional buildings. User activities were determined and tested primarily by existing ontologies and SUA methods [5, 7].

2. Literature Review

The authors reviewed the concept of ontology and representations of user activity and space, which provided useful background knowledge for this study. In addition, the authors examined a number of current SUA studies, upon which this research builds.

2.1. The Concept of Ontology and Its Related Studies Using BIM Techniques. Ontology has been described as "an explicit and formal specification of a conceptualization" [9]. Theoretically, an ontology represents a shared understanding of a domain interest and provides a formalized and machine-readable model of the domain [10]. Numerous applications in information management and integration systems have been developed using ontologies that artificial intelligence applies when capturing knowledge and creating knowledge-based models [11]. Recently, many business and scientific domains have adopted ontologies for sharing, reusing, and processing domain knowledge [11]. The construction industry has also developed domain ontologies such as Industry Foundation Classes (IFC) to improve knowledge management and workflow by establishing a comprehensive data exchange set.

Recently, various studies have been conducted on representing domain knowledge in BIM models using ontologies. Jeong [12] demonstrated building information management using BIM to represent the connectivity of non-BIM data and convert those data into an ontology. Zhang et al. [11] researched a construction safety ontology for organizing, storing, and reusing construction safety knowledge. That study demonstrated the interaction between a safety ontology and BIM. In addition, researchers have employed a building energy ontology using BIM and a Modelica language for building thermal analysis. Other researchers developed the ModelicaBIM library for BIM-based energy analysis and a framework enabling BIM models to be automatically translated into building energy models [13–15].

2.2. Knowledge about Representing User Activity and Space. Text formats (i.e., natural language) are frequently used in the documentation of user activities and space details. Although such representations are convenient for professionals seeking to communicate with one another, they are not compatible with computer modelling and automatic recognition due to their inherent ambiguity [7, 16]. In contrast, ontology is a systematic and explicit method for professionals to use when representing expertise that can be stored and analyzed later through computer modelling [7, 17].

Many studies have modeled construction activities via ontologies, in areas such as automated planning [18, 19], cost estimation [20], field instruction generation [21], and the analyses of time-space conflicts [17]. Darwiche et al. [19] specified the difference between activity and action classes through ontology formalization. Other researchers added spatial requirements to represent construction activities

[17, 20]. Many research efforts have created user simulations for building activity representation, such as modelling emergency evacuation plans [22], assessing building performance [23], and evaluating environmental effects [24]. However, these studies have focused more on individual users than the activity concept (i.e., the precursor of the user concept). Therefore, the direct use of these SUA methods cannot fully represent user activity. To do so in space utilization prediction [4, 7, 25, 26], the current research utilized activity properties (i.e., frequency, duration, user, activity load, sound insulation, and visual privacy). One study distinguished designated space-use from nondesignated space-use, specifying that the subclasses of spatial requirements allowed for flexible space SUA [7]. However, an unstructured combination of existing knowledge cannot form an appropriate set of properties that distinguishes flexible from nonflexible space-use in SUA. Therefore, the current SUA process for flexible space still requires architects to conduct ad hoc analyses, especially when user activities change.

Many researchers have developed space representations that incorporate the dynamic nature of flexible spaces. One developed dynamic layout could be used in planning for temporary facilities on construction sites [27]. Another represented a construction site using a spreadsheet with grid units, in which space area was calculated by combining the unoccupied components [28]. Yet, others utilized sets of space properties such as space type, area, and number, as well as equipment number and area, to enhance space management practices [4, 26]. The changeable space representations in these earlier studies provided a useful background for the current research and inspired the idea of dividing flexible space into appropriate configurations to accommodate different activities.

2.3. Flexible Space in Current Space-Use Analysis Studies. Although studies related to SUA have provided useful theories such as architectural programming [29] and postoccupancy evaluation [30], these have been subject to a significant limitation. Utilization cannot be quickly and consistently tracked or updated when information about the users' activities or spaces changes. To deal with this problem, in [4], the workplace planning theory was introduced, which can be applied during project development. The workplace planning theory determines space utilization on the basis of user activities that are manually linked to a set of building spaces. To automate the mapping between these user activities and spaces and the utilization analysis of the project information, Kim et al. [5] developed an automated SUA based on [4], which provides basic knowledge for computer-aided SUA. However, because a changeable configuration of space is not available in the current automated SUA, SUA for flexible spaces remains an ad hoc process.

To deal with this challenge, Chen and Kim [31] identified the characteristics of user activities by considering the space-use of flexible spaces and used these characteristics as precursors to define seven space-use type differentiators (SUTDs). The goal was to distinguish between flexible and nonflexible space-use. A mapping method was also developed based on these findings that maps user activities onto both flexible and nonflexible spaces and generates activity-space pairs with an algorithm in order to determine the number of usable units of a flexible space that are needed to support a certain activity. However, although this advance is available in automated SUA, activity and space ontologies for capturing flexible space-use and representing flexible space have not yet been defined and employed in automated SUA. Therefore, architects still cannot systematically and explicitly capture activity and flexible space information. As a result, automated SUA implementation for flexible space has still not been developed, and thus the utilization calculation of flexible space cannot be automated, nor the potential of automated SUA in the flexible space domain realized.

3. Methodology

To develop the activity and space ontologies, this study followed the ontology development guidelines proposed by Noy and McGuinness [32] and then defined the two ontologies based on a literature review, case studies, and interviews with architects. Classes and properties were defined to create an activity ontology that captures both flexible and nonflexible space-uses and a space ontology that represents both flexible and nonflexible spaces. These ontologies were further elaborated upon by defining the facets of each property (i.e., cardinality, value type, and range of value types). The validation tasks were already available in earlier research [7, 17, 20, 33] and conducted to measure real-world achievements. The validation method was adopted to test the formality and comprehensiveness of the two ontologies presented here, by representing user activities and spaces in four different cases to determine whether they accommodated seven SUTDs defined in earlier work [31]. Six architects were invited to participate in this test. Since this study developed a prototype of an automated SUA in which the activity and space ontologies function as data input templates, their reproducibility was tested in an automated SUA application.

To enable implementation of the proposed ontologies, this study defined a framework for an automated SUA that would deal with flexible space based on the abovementioned seven SUTDs [31], certain ontological relationships, the developed mapping method [31], and concepts related to utilization prediction [4, 5, 29]. A charrette test was then set up to test the framework's effectiveness via utilization prediction in two separate cases (i.e., an office building and an institutional building). The test was accomplished by comparing the innovative method (i.e., performing an SUA on trials using the prototype) to the conventional process (i.e., manually performing an SUA on the trials) [34]. Each case was predicted by three architects in three trials, including one initial prediction and two updates. The architects performed the three trials by following both processes. As in Clayton et al.'s work [34], comparison of the two processes for each case was based on the time spent and consistency of the results of the utilization predictions. The flowchart in Figure 1 shows the flow of research methodology and clarifies the relationship of each step.

4. Results and Validation

The activity ontology was extended from a previous model developed by Kim and Fischer, which developed the user activity representation as <User>, <Action>, and <Spatial requirement> [7]. The ontology for representing building space (i.e., flexible and nonflexible spaces) was newly developed in this study to provide an explicit representation of both flexible and nonflexible spaces for SUA. In addition, the implementation process for an automated SUA was also clarified with a prototype system capable of predicting the utilization of flexible space.

4.1. Ontologies Representing User Activities and Spaces. In this research, a new <Space requirement> class in the user activity ontology was defined by adding properties that derived the spatial requirements for an activity. These could then be used to distinguish flexible from nonflexible space-uses. The properties' address issues such as sound insulation, visual privacy, furniture rearrangement, and whether flexible space are allowable. <User activity> was further classified into <Typical activity> and <Atypical activity>. The ratio in <Typical activity> represents the proportion of a user group that will participate in the activity, whereas the frequency of <Typical activity> indicates the number of occurrences of a user participating in the activity per day [7]. The <User>, the driver of the activity is further classified as <Regular user> (i.e., one who needs a space that satisfies only the minimum spatial requirements of the user activity, called a constraint) or <Important user> (i.e., one who needs a space that must satisfy the spatial requirements for better performance of the user activity, called a preference). The <Action> is a short description of what the user will do in the space. The extended area, <Spatial requirement>, indicates what a user activity requires in order to occupy the space. The spatial requirement is further classified into <Whole room use requirement> (i.e., what a user activity requires to occupy the whole room) and <Equipment use requirement> (i.e., what a user activity requires to occupy only a part of the room, such as a cubicle within an office).

The newly developed space ontology includes properties that describe various features and attributes of a space, as well as restrictions on those properties (i.e., cardinalities, value types, and ranges). In this study, the space ontology abstracted the nonflexible and flexible space descriptions and associated them with their use. To be specific, space was further classified into <Flexible space>, which can quickly be changed via movable components (e.g., walls and partitions), and <Nonflexible space>, which cannot [31]. In addition, a space has one or both of the following space-uses: <Whole room use>, which supports a user activity that requires an entire room, and <Equipment use>, which supports a user activity that requires only a part of a room (e.g., a cubicle in an office).

In this research, a survey of 12 architects from Hong Kong and mainland China, with an average of five years of experience in the construction industry and just over four years in SUA, was conducted to select the newly identified properties (i.e., properties in the user activity ontology related to sound insulation, visual privacy, furniture rearrangement, and whether flexible space is allowable). The architects were asked to rate their level of agreement with these properties on a 5-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree). All properties received average scores greater than 4.0, suggesting that all properties were accepted and should be dealt with as spatial requirements in the SUA. Note that the consideration of flexible space in the SUA multiplies the number of possible space-use types by roughly four (i.e., increasing the total from 288 to 1,088), as discussed by [31].

As shown in Figure 2, all properties (including the cardinalities, value types, and ranges of value types) of the user activities, users, and action classes followed the definitions provided in [7], which will not be detailed in this research. There were 13 common properties used in the space ontology and spatial requirement class of user activity ontology as summarized in Table 1.

(i) *Space Type*. In the user activity ontology, this property represents the specific type of space that an activity occupies (e.g., a small classroom). According to [7, 35], this differs from the space instance (e.g., classroom Y4302) in the design model. In the space ontology, this functions to identify a space class (e.g., a small classroom). A space type should be unique to distinguish it from others [36].

(ii) *Space Super-Type*. In both the user activity and space ontologies, this property represents the super-type of a space type (e.g., a classroom) that includes one or more space types.

(iii) *Designation*. In the user activity ontology, this property indicates whether or not an activity requires a designated space. In the space ontology, this property characterizes whether the space is already designated for a user activity. If the space is designated for an activity, it is not available for other activities.

(iv) *Sound Insulation Degree*. In the user activity ontology, this property characterizes the degree of sound insulation required by a user activity, based on the user's needs and wants. For this property, the authors interviewed 12 experienced architects. From their opinions, it was clear that sound insulation of 55 dB or more is more expensive than regular insulation. Therefore, only activities sensitive to noise and that require a high degree of conversational privacy should require spaces designed above this threshold, such as meeting rooms in law chambers, hedge fund companies, and banks. Sound insulation of 50 to 54 dB is usually sufficient for

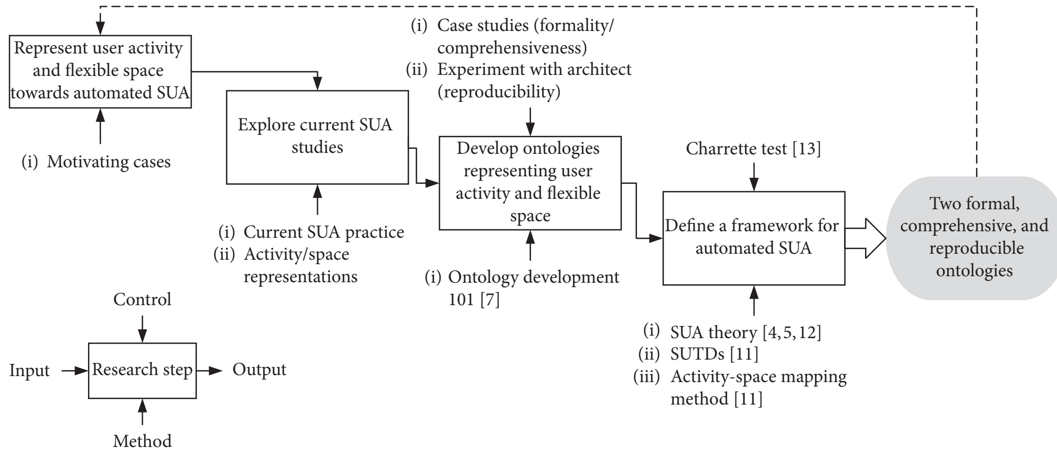


Figure 1: Flowchart of the research methodology.

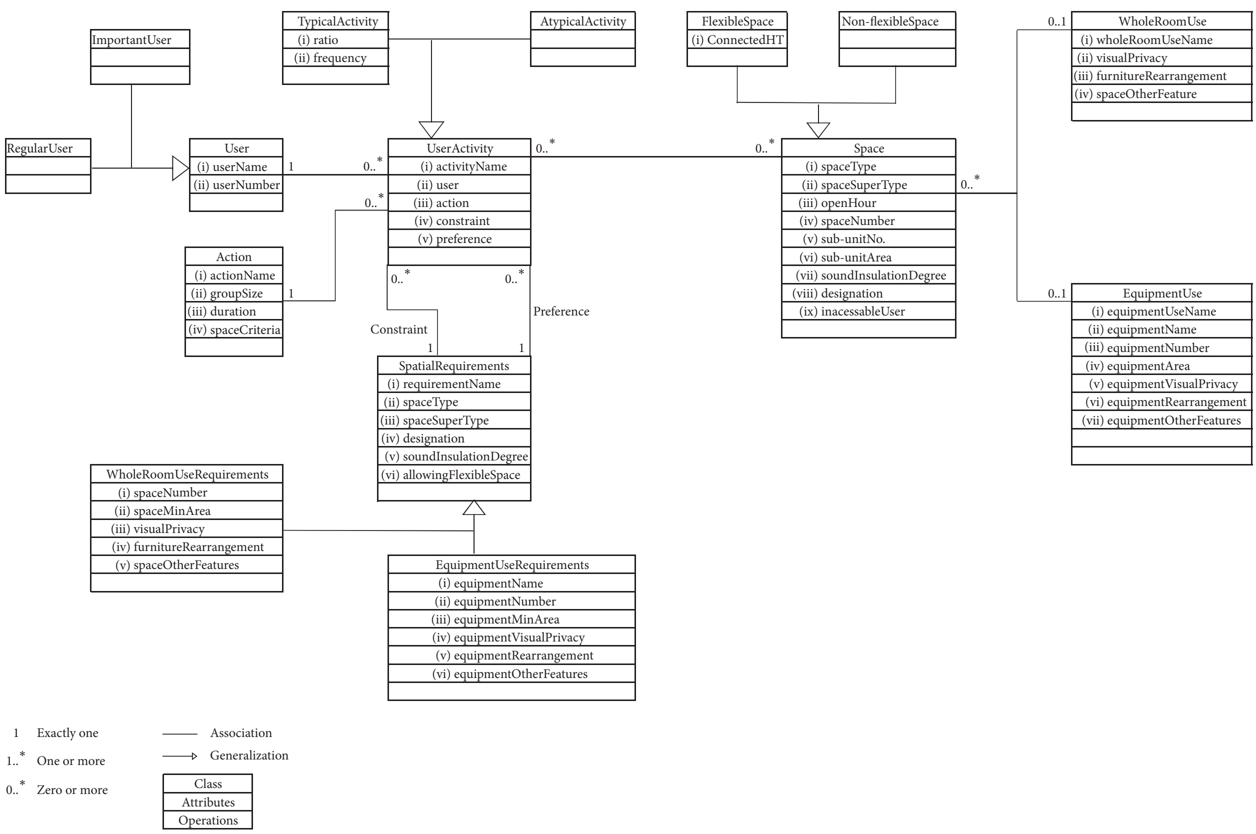


Figure 2: Ontologies representing user activities and space in space-use analysis.

Table 1: Properties and Facets of the <Spatial requirement>, <Whole room use requirement>, and <Equipment use requirement> classes.

Property	Cardinality	Value type	Range
Properties in <Spatial requirement> class			
Requirements name	{1 : 1}	String	\
Space type	{0 : ∗}	Instance	Space type
Space super-type	{0 : ∗}	Instance	Space super type
Designation	{1 : 1}	Boolean	True, false
Sound insulation degree	{1 : 1}	Interval	≤39 dB, 40–44 dB, 45–49 dB, 50–54 dB, ≥55 dB
Allowing flexible space	{1 : 1}	Boolean	True, false

Table 1: Continued.

Property	Cardinality	Value type	Range
Properties in <Whole room use requirement> class			
Space number	{0 : 1}	Integer	Positive
Space minimum area	{0 : 1}	Float	Positive
Visual privacy	{1 : 1}	Boolean	True, false
Furniture rearrangement	{1 : 1}	Boolean	True, false
Other space features	{0 : ∗}	Instance	Feature
Properties in <Equipment use requirement> class			
Equipment name	{0 : ∗}	Instance	Equipment
Equipment number	{0 : 1}	Integer	Positive
Equipment minimum area	{0 : 1}	Float	Positive
Equipment visual privacy	{1 : 1}	Boolean	True, false
Equipment rearrangement	{1 : 1}	Boolean	True, false
Equipment other features	{0 : ∗}	Instance	Feature

teaching activities and speeches, to prevent these kinds of activities from affecting those occurring in adjacent spaces. Sound insulation of 45 to 49 dB is required for activities that do not require conversational privacy. In such environment, voices can be heard but not understood in adjacent spaces. Sound insulation of 40 to 44 dB is sufficient for activities such as normal staff training, but sound insulation of 39 dB or less is inadequate for activities such as self-study. Based on the experts' feedback, "Guidance on sound insulation and noise reduction for buildings" [37] and "Acoustic design of schools: Performance standards" [38], five scales of sound insulation were applied in this research, as shown in Table 1. In the space ontology, this property signifies the degree of sound insulation used in a space (e.g., 44 dB).

(v) *Space Number*. In the user activity ontology, this property represents the amount of space that a user activity requires. In the space ontology, this property signifies the amount of a particular space type.

(vi) *Visual Privacy*. In the user activity ontology, this property denotes whether an activity requires a space that can guarantee visual privacy. In the space ontology, this property indicates whether or not a space can guarantee visual privacy.

(vii) *Furniture Rearrangement*. In the user activity ontology, this property represents whether an activity requires a space that provides rearrangeable furniture. In the space ontology, this property denotes whether a space provides rearrangeable furniture.

(viii) *Other Space Features*. In the user activity ontology, this property signifies the features of a space required for an activity, such as multimedia facilities. In the space ontology, this property represents the features of a space.

(ix) *Equipment Name*. In the user activity ontology, this property represents the specific name of the equipment required for an activity, such as workstation or cubicle. In the space ontology, this property signifies the specific name of the equipment that a space provides.

(x) *Equipment Number*. In the user activity ontology, this property indicates the amount of equipment that a user activity requires. In the space ontology, this property shows the amount of equipment that a space provides.

(xi) *Equipment Visual Privacy*. In the user activity ontology, this property indicates whether an activity requires a piece of equipment (e.g., a cubicle with partitions installed) to guarantee visual privacy. In the space ontology, this property specifies whether the equipment can guarantee visual privacy.

(xii) *Equipment Rearrangement*. In the user activity ontology, this property represents whether an activity requires a piece of rearrangeable equipment. In the space ontology, this property signifies whether the equipment provided can be rearranged.

(xiii) *Other Equipment Features*. In the user activity ontology, this property denotes the features the activity requires of a piece of equipment. In the space ontology, this property denotes the features of a piece of equipment.

The other properties related to the spatial requirements of the user activity ontology are defined as follows. The properties and facets of the <Spatial requirement>, <Whole room use requirement>, and <Equipment use requirement> classes are summarized in Table 1.

(i) *Requirement Name*. This functions as an identification of the requirement class (e.g., Constraint 1 or Preference 1). An user activity's requirement name should be unique to distinguish it from others [36].

(ii) *Flexible Space Allowe*d. This property indicates whether a user activity is allowed in a flexible space. When the value is "true," the activity can be accommodated by a flexible space, and when the value is "false," it cannot.

(iii) *Space Minimum Area*. This property signifies the minimum space area that an activity requires. When the space's minimum area is not specified in the spatial requirement (i.e., <Whole room use requirement>), the automated SUA will use the values for space criteria (under the <Action> class) and group size (under the <Action> class) to automatically estimate the minimum space area needed (i.e., space criteria ∗ group size).

(iv) *Equipment Minimum Area*. This property signifies the minimum area required for a piece of equipment needed for an activity. When the equipment's minimum area is not specified in the spatial requirement (i.e., <Equipment use requirement>), the automated SUA will use the value of the space criteria (under the <Action> class) and group size (under the <Action> class) to automatically estimate the minimum area necessary (i.e., space criteria ∗ group size).

The other properties in the space ontology are defined as follows. The properties and facets of the <Space>, <Whole room use>, and <Equipment use > classes are summarized in Table 2.

(i) Open hour: This property indicates the number of hours per day that a space is available for use.

(ii) Subunit number: This property represents the number of subunits that form a flexible space. In a nonflexible space, only one subunit is available.

(iii) Subunit area. This property indicates the area of each subunit of a space.

(iv) Inaccessible user: This property denotes user groups that are not allowed to access the space.

(v) Connected HT (i.e., connected head and tail subunits): This property represents a type of flexible space in which the head subunit either shares a movable component with the tail subunit (i.e., value: true) or does not (i.e., value: false). Both types were described by [31].

(vi) Whole room use name: This functions as an identification of the whole room use class (e.g., S1W). It should be unique to distinguish it from others [36].

(vii) Equipment use name: This functions as an identification of the equipment use class (e.g., S1E). It should be unique to distinguish it from others [36].

(viii) Equipment area: This property denotes the area taken up by a piece of equipment.

Table 2: Properties and Facets of the <Space>, <Whole room use>, and <Equipment use> classes.

Property	Cardinality	Value type	Range
Properties in <Space> class			
Space type	{1 : 1}	Instance	Space type
Space super type	{1 : 1}	Instance	Space super type
Open hour	{1 : 1}	Float	Positive
Space number	{1 : 1}	Integer	Positive
Subunit number	{1 : 1}	Integer	Positive
Subunit area	{1 : 1}	Float	Positive
Sound insulation degree	{1 : 1}	Integer	Positive
Designation	{1 : 1}	Boolean	True, false
Inaccessible user	{0 : ∗}	Instance	User
Properties in Flexible space			
Connected HT	{1 : 1}	Boolean	True, false
Properties in <Whole room use> class			
Whole room use name	{1 : 1}	String	\
Visual privacy	{1 : 1}	Boolean	True, false
Furniture rearrangement	{1 : 1}	Boolean	True, false
Other space features	{0 : ∗}	Instance	Feature
Properties in <Equipment use> class			
Equipment use name	{1 : 1}	String	\
Equipment name	{1 : 1}	String	\
Equipment number	{1 : 1}	Integer	Positive
Equipment area	{1 : 1}	Float	Positive
Equipment visual privacy	{1 : 1}	Boolean	True, false
Equipment rearrangement	{1 : 1}	Boolean	True, false
Equipment other features	{0 : ∗}	Instance	Feature

4.2. Implementation Process of the Automated Space-Use Analysis for Flexible Space. This implementation process enables the (1) automatic generation of activity-space pairs by mapping user activities onto appropriate spaces and (2) automatic calculation of utilization based on the pairs available and certain operation prediction theories [4, 5, 29]. This framework was developed based on (1) SUA concepts [4, 5, 29], (2) seven SUTDs that distinguish space-use types for SUA [31], (3) a method for mapping user activities onto both flexible and nonflexible spaces [31], and (4) activity and space ontologies that capture the necessary flexible and nonflexible space-uses of user activity and the information necessary for both flexible and nonflexible spaces, respectively. A prototype system (see Figure 3 represented as a unified modelling language activity diagram) was created and used in the validation of this research, in order to examine the reproducibility of the developed ontologies and test the effectiveness of the automated SUA. The prototype system was developed in power builder, an integrated application development environment. The implementation process for the automated SUA had three steps (Figure 4): "entering project data (input)," "mapping user activities onto space (analysis)," and "computing utilization (output)."

Step 1. Entering project data (input)

The architect enters the data based on the user profiles and space information. The two ontologies described in this research function as data input templates. The architect can enter the necessary data based on the ontologies, even without background knowledge of them. The computer gathers and stores these data and feeds them into Steps 2 and 3 (i.e., mapping and computing utilization) after the architect finishes entering the data.

Step 2. Mapping user activities onto spaces (analysis)

When the input (i.e., activity and space information) is available, the computer uses it to analyze (i.e., map user

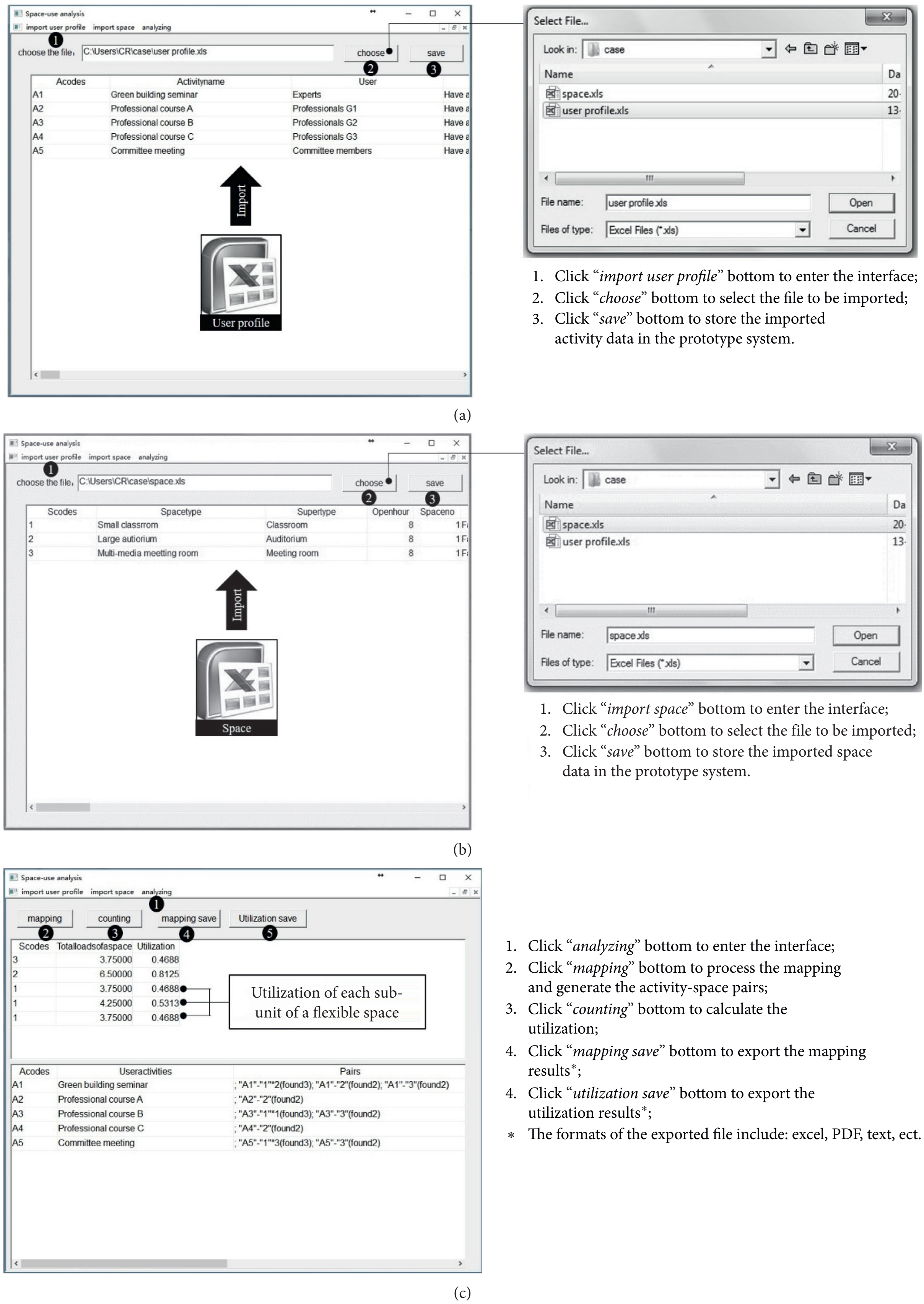


Figure 3: Prototype system for an automated SUA. (a) Import activity information. (b) Import space information. (c) Mapping and computing utilization.

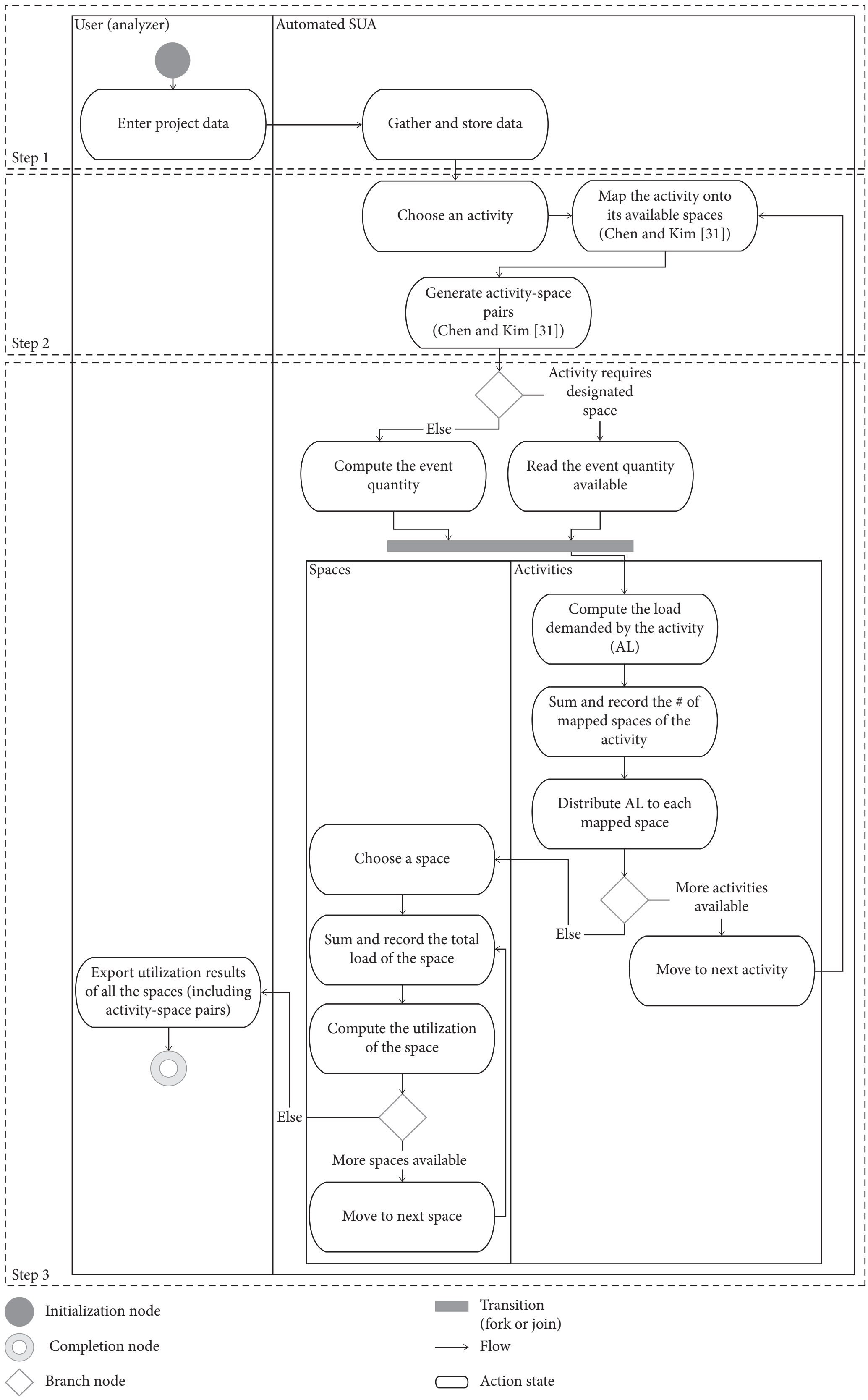


Figure 4: Implementation process for the automated SUA.

activities onto appropriate flexible or nonflexible spaces) and generate activity-space pairs. This activity-space mapping proceeds without human interpretation and includes choosing spatial requirements, finding appropriate space, computing usable units for flexible space, and mapping activities onto the available space [31].

Step 3. Computing utilization (output)

When the input from Step 1 and activity-space pairs from Step 2 are available, the computer can prepare its output (i.e., calculate the utilization based on utilization prediction theories [4, 5, 29]). The process for this step is as follows:

Step 3.1. Processing analysis related to user activity

Step 3.1.1. Compute the load demanded by an activity, which indicates the number of hours that an activity requires from its mapped spaces. The event quantity must be calculated before computing the load demanded. The event quantity refers to the number of user groups for a given user activity. For activities that require a designated space, the computer will read the value of the event quantity from Step 2 because it is calculated before the activity is mapped onto its designated spaces. For activities that do not require a designated space, the computer will calculate the event quantity. The formulas used are as follows [4]:

$$\text{event quantity} = \frac{(\text{the number of users of an activity} * \text{the ratio of an activity})}{\text{the group size of the action of an activity}},$$
$$\text{load demanded by an activity} = \text{event quantity of an activity} * \text{the frequency of an activity} * \text{the duration of an activity}. \quad (1)$$

Step 3.1.2. Sum and record the number of mapped spaces (or equipment) for an activity.

Step 3.1.3. Evenly distribute the load demanded for an activity to each of its mapped spaces (or equipment) by dividing "the load demanded for an activity" by "the number of mapped spaces (or pieces of equipment)."

Step 3.1.4. Move to the next activity and repeat Phases 1.1 to 1.4 if more activities are available.

Step 3.2. Processing analysis related to spaces and predictions:

Step 3.2.1. Sum and record the total space load: for nonflexible spaces, the total space load is computed by summing the loads of all mapped activities, including activities mapped onto the space and those mapped onto pieces of equipment that belong to that space. For flexible spaces, the total load is computed by separately considering each subunit. That is, the total load of each subunit of a flexible space is computed by summing the loads of all mapped activities, including activities mapped onto the subunit and those mapped onto pieces of equipment belonging to that subunit.

Step 3.2.2. Compute the utilization of space: for nonflexible space, the utilization is computed by dividing the "total space load" by the "open hours." For flexible space, utilization also separately considers each subunit (i.e., the utilization of each subunit of a flexible space is computed by dividing the "total load of each subunit of a flexible space" by the "open hours").

Step 3.2.3. Move to the next space and repeat Phases 2.1 and 2.2 if more spaces are available.

Step 3.3. Export and save the utilization results (including the generated activity-space pairs).

4.3. Validation. The activity and space ontologies defined in this study were tested on four cases to determine their formality and comprehensiveness [7, 17, 20]. In addition, a prototype automated SUA was developed, and the reproducibility of the two ontologies tested on two cases via the automated SUA [33]. A charrette test was also conducted to validate the effectiveness of the context of the automated SUA [34].

4.3.1. Formality of the Ontologies. Four case studies were conducted to validate the formality of the activity and space ontologies. Two were office projects (Cases 1 and 2) in Shenzhen, China. Confidentiality constraints prevent the disclosure of their names. The other two cases were institutional buildings: Cygnaeus High School (Case 3), based on [4], and an Integrated Teaching (AIT) building (Case 4) at the Chinese University of Hong Kong, developed via observation. The user activities, flexible spaces, and nonflexible spaces identified from these four cases were represented using the proposed activity and space ontologies (Table 3). The authors invited six architects with an average of fifteen years of industry experience to participate. Three were involved in the two institutional cases, and the other three participated in the two office cases. The results of these four case studies show the formality of the activity and space ontologies because 20 user activities, 10 non-flexible spaces, and four flexible spaces were all successfully represented. The 20 user activities represented nine types of space-use, four of which captured flexible space-use. Two types of flexible space were formally represented using the space ontology.

4.3.2. Comprehensiveness of the Ontologies. The activity and space ontologies were proven to be sufficiently comprehensive because the proposed activity ontology captured

Table 3: Cases for validation of the ontologies.

Case id	Building type	Number of activities	Number of nonflexible spaces	Number of flexible space included
1	Office	5	2	1 (with two subunits)[1]
2	Office	5	3	1 (with two subunits)[1]
3	Institutional	5	3	1 (with four subunits)[2]
4	Institutional	5	2	1 (with six subunits)[1]

Note. [1]A flexible space whose head subunit does not share a movable component with the tail subunit. [2]A flexible space whose head subunit shares a movable component with the tail subunit.

seven SUTDs and the proposed space ontology captured information related to both flexible and nonflexible spaces, corresponding to four of the seven SUTDs (i.e., those related to the spatial requirements of user activity). Specifically, the <User activity> class of the activity ontology was further classified into <Typical activity> and <Atypical activity>, which considered SUTD 1 (i.e., typical activity vs. atypical activity). The <User> class of the activity ontology was further classified into <Important user> and <Regular user>, which considered SUTD 2 (i.e., important user vs. regular user). The properties of constraint and preference were available for instances of <Spatial requirements> in the activity ontology, which considered SUTD 3 (i.e., situations in which the space preference and constraints are the same vs. those in which they differ). The property of designation was available in the <Spatial requirement> class of the activity ontology, and the property representing the designation status was available in the <Space> class of the space ontology, both of which considered SUTD 4 (i.e., situations in which an activity requires a designated space vs. those in which it does not).

The <Spatial requirement> class of the activity ontology was further classified into <Whole room use requirement> and <Equipment use requirement>, and the <Space> class of the space ontology had space-uses—<Whole room use> and <Equipment use>—that considered SUTD 5 (i.e., situations in which an activity requires a whole room vs. those in which only a part of a room is necessary). The space super-type property and properties that represent the space's features were available in the <Spatial requirement > of the activity and space ontologies, both of which considered SUTD 6 (i.e., situations in which an activity requires a specific type of space vs. those in which only the required features of the appropriate space are specified). The property that indicates whether a user activity can be accommodated by a flexible space was available in the <Spatial requirement > of the activity ontology, and the <Space> class was further classified into <Flexible space> and <Nonflexible space>, both of which considered SUTD 7 (i.e., situations in which an activity allows for the use of a flexible space vs. those in which it does not).

4.3.3. Reproducibility of the Ontologies. To test the reproducibility of the developed ontologies, it was necessary to determine if different architects could obtain consistent results from the automated SUA, using the proposed ontologies to represent the same case as input. Thus, the activity and space ontologies were implemented in a prototype of the automated SUA via the innovative process of the charrette test introduced in the next section. As a result, it was determined that the utilization data from the architects using the innovative process for Cases 2 and 3 were consistent with one another, which was demonstrated via the successful use of the proposed activity ontology to represent the user activities and proposed space ontology, with both flexible and nonflexible spaces used as input for the prototype automated SUA. This implies the reproducibility of the activity and space ontologies such that different architects should be able to use them to model the same activities and spaces (both flexible and nonflexible) and obtain consistent results.

4.3.4. Effectiveness of the Automated SUA. To validate the effectiveness of the automated SUA's framework, a charrette test (Figure 5) was conducted, following the definition provided in [34]. A prototype system was developed to automatically predict and update the utilization of both flexible and nonflexible spaces. Case 2 (i.e., the office case) and Case 3 (i.e., the institutional case of Cygnaeus High School) were used in this test. Three architects (i.e., Group 1, with an average of 16.3 years of work experience) were invited to test Case 2, and another three (i.e., Group 2, with an average of 13.7 years of work experience) were invited to test Case 3. There were three user activities, one flexible space and two nonflexible spaces in each. Two flexible space types [31] were included in each case.

Based on the intent of the charrette test, the testing of each case included three trials. The first predicted the space utilization based on three user activities and three nonflexible spaces. The second trial updated the space utilization based on changes in the space information (i.e., the spaces were updated to have one flexible space and two nonflexible spaces). The third trial updated the space utilization based on changes in the activity information (i.e., the spatial requirements of the user activities were updated). The architects from Groups 1 and 2 performed three trials, first via the conventional method (i.e., manually performing SUAs of the trials) and then using the innovative method (i.e., using the prototype to perform SUAs of the trials). In both cases, the propositions (i.e., the time spent and consistency of the results) necessitated specific measurements of each architect's performance using the two processes.

The charrette results suggested that the automated SUA (i.e., the innovative method), for which no human interpretation was needed in the utilization prediction, was more effective. Tables 4 and 5 show the time spent on the three trials for Cases 2 and 3. The average time spent using the innovative method for Case 2 (i.e., 11.08 minutes = 9.05 minutes + 1.08 minutes + 0.95 minutes) was much less

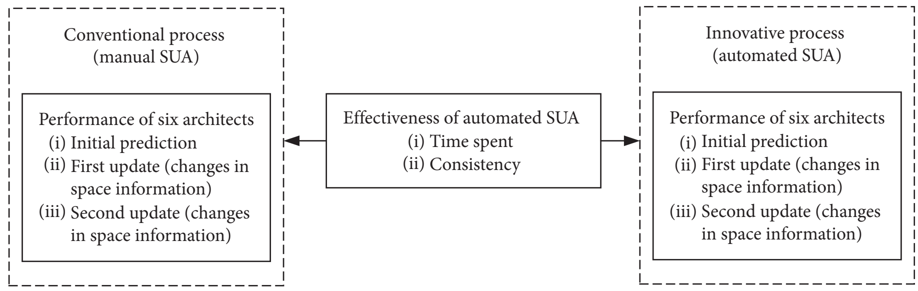


Figure 5: Charrette test design.

Table 4: Time spent on Case 2.

Participants	Experience (years)	Time for conventional process (min)			Time for innovative process (min)		
		Initial prediction	First update	Second update	Initial prediction	First update	Second update
Architect 1	6	18.72	9.27	3.85	8.37	1.05	0.92
Architect 2	13	17.02	9.4	4.05	9.8	0.93	0.96
Architect 3	30	17.2	8.11	3.25	8.97	1.28	0.95
Average	16.3	17.64	8.93	3.72	9.05	1.08	0.95

Table 5: Time spent on case 3.

Participants	Experience (years)	Time for conventional process (min)			Time for innovative process (min)		
		Initial prediction	First update	Second update	Initial prediction	First update	Second update
Architect 4	8	21.95	14.88	10	11.2	0.87	0.6
Architect 5	5	17.55	14.67	12.05	8.3	0.74	0.59
Architect 6	28	14.88	13.17	7.86	8.5	0.8	0.7
Average	13.7	18.13	14.24	9.97	9.33	0.8	0.63

than the average time spent using the conventional method (i.e., 30.29 minutes = 17.64 minutes + 8.93 minutes + 3.72 minutes). Thus, the innovative process for Case 2 was 2.7 times faster. The average time spent for Case 3 using the innovative method (i.e., 10.76 minutes = 9.33 minutes + 0.8 minutes + 0.63 minutes) was much less than the average time spent using the conventional method (i.e., 42.34 minutes = 18.13 minutes + 14.24 minutes + 9.97 minutes). Thus, the innovative process for Case 3 was 3.9 times faster. The reasons why the innovative process was faster were that the architects did not need to manually distinguish different flexible and nonflexible space-use types, map activities onto nonflexible and flexible spaces with the appropriate configurations, and calculate the data needed (e.g., activity load, and space load) to predict the utilization.

To show that the charrette test reduces the effects of learning that can occur when subjects repeat tasks of the same case (i.e., perform an SUA first with the conventional and then with the innovative methods), the time spent by each architect during each trial was measured in each of two separate parts. For the conventional process, these two parts were comprised of the time needed to comprehend the material regarding the activities and spaces (i.e., the three architects in Case 2 averaged a total of 7.39 minutes for the three trials, while the three architects in Case 3 averaged a total of 10.55 minutes for the same) and the time required for separate manual utilization calculations. With regards to the innovative process for each trial, the two parts were comprised of the time needed to enter the data on the activities and spaces (i.e., the three architects in Case 2 averaged 10.11 minutes in total for the three trials, while the three architects in Case 3 averaged a total of 9.85 minutes for the same) and the time needed for the utilization calculation via the prototype. Neither Case 2 nor 3 saw significant reduction compared to the time needed to comprehend the material by those entering the data. In terms of generality, the charrette test included the utilization use predictions for three trials of one institutional case and three trials of one office case.

In terms of measuring the consistency of the results, the mean absolute deviation (MAD) [39] was used. The MAD of a group of utilization results for a certain space is obtained by measuring the average distance between each architect's utilization value and the mean. The MAD analysis of Cases 2 and 3, shown in Tables 6 and 7, suggests that the innovative process with the automated SUA was relatively consistent among all trials. The reasons why the innovative process would be more consistent are that the architects did not need to manually analyze the flexible spaces with appropriate configurations, calculate the activity load, assign the activity load to the mapped space, and calculate the utilization. Thus, this innovative process with standardized activity and space representations will reduce the probability of manual errors and contribute to a consistent result. Therefore, the automated SUA can be considered more reliable as the ontologies help analysts accurately capture a project's important information (i.e., activity and space) and therefore consistently predict and update the uses of both flexible and nonflexible spaces.

Table 6: MADs of the three Case 2 trials.

Space		MAD of conventional process (%)	MAD of innovative process
Initial prediction			
Space 1		0.53	0
Space 2		4.84	0
Space 3		7.90	0
First update			
Space 1[1]	Subunit 1	2.58	0
	Subunit 2	2.95	0
Space 2		2.56	0
Space 3		7.90	0
Second update			
Space 1[1]	Subunit 1	2.58	0
	Subunit 2	2.95	0
Space 2		0.92	0
Space 3		26.76	0

[1]A flexible space whose head subunit does not share a movable component with the tail subunit.

Table 7: MADs of the three Case 3 trials.

Space		MAD of conventional process (%)	MAD of innovative process
Initial prediction			
Space 1		10.12	0
Space 2		0.72	0
Space 3		0.85	0
First update			
Space 1		17.13	0
Space 2[1]	Subunit 1	0.43	0
	Subunit 2	0.43	0
	Subunit 3	0.43	0
	Subunit 4	0.43	0
Space 3		6.42	0
Second update			
Space 1		14.94	0
Space 2[1]	Subunit 1	0.32	0
	Subunit 2	0.32	0
	Subunit 3	0.32	0
	Subunit 4	0.32	0
Space 3		20.50	0

[1]A flexible space whose head subunit shares a movable component with the tail subunit.

5. Conclusions

Research efforts have been made to extend the current SUA method in order to more quickly and consistently examine the performances of different design options in terms of flexible-space utilization. In a previous study [31], researchers developed a method for mapping user activities onto flexible spaces. However, current activity and space representations are not available to provide architects with a common vocabulary for capturing flexible space-use and abstracting the information accompanying the use of flexible space. In addition, a framework for the implementation process for an automated flexible-space SUA had not yet been developed. To make use of the previously developed mapping method [31] and achieve a potential automated SUA for the flexible space domain, this study defined (1) an activity ontology containing 10 classes and 32 properties and a space ontology containing five classes and 22 properties, and (2) a framework for formalizing an automated SUA implementation process to deal with utilization predictions for flexible space.

The activity and space ontologies are novel because they allow a computer to gather the information necessary to distinguish among different flexible and nonflexible space-use types and predict the utilization of both flexible and nonflexible spaces based on the developed implementation framework of an automated SUA. These are not available in current theories of user activity and space representation, which require architects to track the information manually for later utilization calculations. The proposed activity and space ontologies have been validated and are considered formal, as 20 user activities, 10 nonflexible spaces, and four flexible spaces from four different office and institutional cases were all successfully represented. To validate this method as comprehensive, seven SUTDs of user activities and information related to both flexible and nonflexible space (corresponding to four of the seven SUTDs that were related to spatial requirements) were captured. Finally, to deem the process as reproducible, the utilizations predicted by three architects in office or institutional cases who used these two ontologies as input for the automated SUA application were found to be consistent with one another.

The proposed framework for this automated SUA implementation process for flexible space is novel because with the assistance of computer and it provides architects with a quick and consistent means of utilization prediction with regards to flexible space. This framework is embedded with (1) SUA concepts [4, 5, 29], (2) seven SUT`Ds that distinguish the different space-use types that must be analyzed in an SUA [31], (3) a method for mapping user activities onto both flexible and nonflexible spaces [31], and (4) activity and space ontologies that capture the necessary flexible space-uses of user activities and the information necessary for flexible space. The three steps include "entering project data (input)," "mapping user activities onto space (analysis)," and "computing utilization (output)." The authors demonstrated its effectiveness by developing a prototype and conducting a charrette test. As the results of the charrette test show, the speed and consistency of utilization prediction are improved with the automated SUA. In terms of generality, the charrette test was conducted on one institutional case (including one initial prediction and two updates) and one office case (including one initial prediction and two updates), with six trials in total. Three architects participated in each case's predictions.

Architects equipped with such an automated SUA will be able to quickly and consistently monitor the space efficiency of building designs and determine the effects of their decisions, such as by adding flexible space to a design, changing the number of subunits of flexible space, and refining the spatial requirements of user activity. The authors plan to extend the representations and SUA to include (1) activities containing a stochastic number of users that affect dividing flexible space into appropriate usable units and (2) flexible spaces that contain different sizes of subunits and a variety of types of movable components to support sustainable building design. In future work, the authors will link the automated SUA with BIM models to develop and visualize flexible space and its movable components and determine how these can be processed to the automated SUA. This research will contribute to performance-based designs by providing an automated method for architects to predict and update the utilization of both flexible and nonflexible spaces during project development, which will improve designs by reducing underutilized or overutilized spaces without losing the planned functions of a building facility.

Data Availability

The data used to support the findings of this research work are available from the authors including the corresponding author based on requests.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (Nos. 2016R1C1B2014542 and 2017R1C1B5075654). This work was supported by the research grant of the Chungbuk National University in 2017.

References

[1] W. McGregor and D. Then, *Facilities management and the business of space*, Routledge, New York, NY, USA, 1999.

[2] M. A. Hassanain, "Factors affecting the development of flexible workplace facilities," *Journal of Corporate Real Estate*, vol. 8, no. 4, pp. 213–220, 2006.

[3] T. J. M. V. D.. Voordt, "Costs and benefits of flexible workspaces: work in progress in The Netherlands," *Facilities*, vol. 22, no. 9-10, pp. 240–246, 2004.

[4] A. Pennanen, *User activity based workspace definition as an instrument for workplace management in multi-user organizations*, Ph.D. Thesis, Dept. of Architecture, Tampere University of Technology, Tampere, Finland, 2004.

[5] T. W. Kim, R. Rajagopal, M. Fischer, and C. Kam, "A knowledge-based framework for automated space-use analysis," *Automation in Construction*, vol. 32, pp. 165–176, 2013.

[6] R. Schmidt III and S. Austin, *Adaptable Architecture: Theory and Practice*, Routledge, New York, NY, USA, 2016.

[7] T. W. Kim and M. Fischer, "Ontology for representing building users' activities in space-use analysis," *Journal of Construction Engineering and Management*, vol. 140, no. 8, pp. 1–9, 2014.

[8] M. Uschold and M. Gruninger, "Ontologies : principles, methods and applications," *The Knowledge Engineering Review*, vol. 11, no. 2, p. 93, 1996.

[9] T. R. Gruber, "Toward principles for the design of ontologies used for knowledge sharing?," *International Journal of Human-Computer Studies*, vol. 43, no. 5-6, pp. 907–928, 1995.

[10] I. Horrocks, "Description logic reasoning," in *Proceedings of the International Conference on Logic Programming and Automated Reasoning*, Montevideo, Uruguay, January 2006.

[11] S. Zhang, F. Boukamp, and J. Teizer, "Ontology-based semantic modeling of construction safety knowledge: towards automated safety planning for job hazard analysis (JHA)," *Automation in Construction*, vol. 52, pp. 29–41, 2015.

[12] Y. Jeong, "A study on the BIM evaluation, analytics, and prediction (EAP) framework and platform in linked building ontologies and reasoners with clouds," *Advances in Civil Engineering*, vol. 2018, pp. 1–14, 2018.

[13] W. Jeong, J. B. Kim, M. J. Clayton, J. S. Haberl, and W. Yan, "Translating building information modeling to building energy modeling using model view definition," *The Scientific World Journal*, vol. 2014, Article ID 638276, 21 pages, 2014.

[14] J. B. Kim, W. Jeong, M. J. Clayton, J. S. Haberl, and W. Yan, "Developing a physical BIM library for building thermal energy simulation," *Automation in Construction*, vol. 50, pp. 16–28, 2015.

[15] W. Jeong, J. B. Kim, M. J. Clayton, J. S. Haberl, and W. Yan, "A framework to integrate object-oriented physical modelling with building information modelling for building thermal simulation," *Journal of Building Performance Simulation*, vol. 9, no. 1, pp. 50–69, 2016.

[16] A. Bernstein and E. Kaufmann, "GINO–a guided input natural language ontology editor," in *Proceedings of the*

International Semantic Web Conference, Athens, GA, USA, November 2006.

[17] B. Akinci, M. Fischer, J. Kunz, and R. Levitt, "Representing work spaces generically in construction method models," *Journal of Construction Engineering and Management*, vol. 128, no. 4, pp. 296–305, 2002.

[18] F. Aalami, R. Levitt, and M. Fischer, "A Customizable Representation for Construction Method Models," in *CIFE Working Paper*, Stanford University, Stanford, CA, USA, 1998.

[19] A. Darwiche, R. E. Levitt, and B. Hayes-Roth, "OARPLAN: generating project plans by reasoning about objects, actions and resources," *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*, vol. 2, no. 03, p. 169, 1988.

[20] S. Staub-French, M. Fischer, J. Kunz, and B. Paulson, "An ontology for relating features with activities to calculate costs," *Journal of Computing in Civil Engineering*, vol. 17, no. 4, pp. 243–254, 2003.

[21] C. Mourgues, M. Fischer, and J. Kunz, "Method to produce field instructions from product and process models for cast-in-place concrete operations," *Automation in Construction*, vol. 22, pp. 233–246, 2012.

[22] X. Pan, C. S. Han, K. Dauber, and K. H. Law, "A multi-agent based framework for the simulation of human and social behaviors during emergency evacuations," *Ai & Society*, vol. 22, no. 2, pp. 113–132, 2007.

[23] J. Dijkstra and H. Timmermans, "Towards a multi-agent model for visualizing simulated user behavior to support the assessment of design performance," *Automation in Construction*, vol. 11, no. 2, pp. 135–145, 2002.

[24] W. Yan and Y. Kalay, "Geometric, cognitive and behavioral modeling of environmental users," in *Design Computing and Cognition'06*, pp. 61–79, Springer, Netherlands, 2006.

[25] S. Cha, *Stochastic space-use prediction in light of spatial choice Behaviour: modelling space preference of work-related activities*, Ph.D. Thesis, Department of Architecture, University of Cambridge, Cambridge, UK, 2015.

[26] V. Tabak, *User simulation of space utilisation: system for office building usage simulation*, Ph.D. Thesis, Eindhoven University, Eindhoven, Netherlands, 2009.

[27] I. D. Tommelein and P. P. Zouein, "Interactive dynamic layout planning," *Journal of construction engineering and management*, vol. 119, no. 2, pp. 266–287, 1993.

[28] T. Hegazy and E. Elbeltagi, "EvoSite: evolution-based model for site layout planning," *Journal of Computing in Civil Engineering*, vol. 13, no. 3, pp. 198–206, 1999.

[29] E. Cherry, *Programming for Design: from Theory to Practice*, John Wiley & Sons, New York, NY, USA, 1999.

[30] A. Zimmerman and M. Martin, "Post-occupancy evaluation: benefits and barriers," *Building Research and Information*, vol. 29, no. 2, pp. 168–174, 2001.

[31] X. B. Chen and T. W. Kim, "Automated mapping of user activities onto flexible space in space-use analysis," *Journal of Construction Engineering and Management*, vol. 143, no. 8, article 04017034, 2017.

[32] N. Noy and D. McGuinness, "Ontology development 101: a guide to creating your first ontology," *Development*, vol. 32, pp. 1–25, 2001.

[33] J. Thomsen, R. E. Levitt, J. C. Kunz, C. I. Nass, and D. B. Fridsma, "A trajectory for validating computational emulation models of organizations," *Computational and Mathematical Organization Theory*, vol. 5, no. 4, pp. 385–401, 1999.

[34] M. Clayton, J. Kunz, and M. Fischer, "The charrette test method," CIFE Technical Report 120, Stanford University, Stanford, CA, USA, 1998.

[35] A. Kiviniemi, *Requirements Management Interface to Building Product Models*, VTT Publications, no. 572, 2005.

[36] G. Booch, *The Unified Modeling Language*, Techniques, 1998.

[37] BS8233, *Guidance on Sound Insulation and Noise Reduction for Buildings*, British Standards Institute, London, UK, 2014.

[38] BB93, *Acoustic Design of Schools: Performance Standards*, The Department of Education, London, UK, 2015.

[39] P. Westfall and K. S. Henning, *Understanding Advanced Statistical Methods*, CRC Press, Boca Raton, FL, USA, 2013.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 8367131, 12 pages
https://doi.org/10.1155/2019/8367131

Research Article

Construction Database-Supported and BIM-Based Interface Communication and Management: A Pilot Project

Yu-Cheng Lin,[1] **Shuh Jung**,[2] **and Yu-Chih Su**[3]

[1]*Professor, Department of Civil Engineering, National Taipei University of Technology, No. 1.Chung-Hsiao E. Rd., Sec.3, Taipei, Taiwan*
[2]*Ph.D. Student, Department of Civil Engineering, National Taipei University of Technology, No. 1.Chung-Hsiao E. Rd., Sec.3, Taipei, Taiwan*
[3]*Ph.D, Department of Civil Engineering, National Taipei University of Technology, No. 1.Chung-Hsiao E. Rd., Sec.3, Taipei, Taiwan*

Correspondence should be addressed to Yu-Cheng Lin; yclinntut@gmail.com

Received 30 November 2018; Revised 28 January 2019; Accepted 19 February 2019; Published 11 March 2019

Guest Editor: Eugenio Pellicer

Construction projects are subject to numerous interface problems, particularly during the construction phase. The absence of suitable systems or platforms to tackle these issues could hinder the performance of construction management. Thus, the communication and management of interfaces (CMI) are necessary to improve the quality of the management of construction projects. E-mail and generic construction information systems are commonly used communication tools; however, they pose several limitations in recording and managing as well as in responding to interface problems. Building information modeling (BIM), by contrast, saves and delivers information in a digital format in a 3D computer-aided design (CAD) environment. The adoption of BIM technology integrated with web technology for construction projects allows users to communicate interface issues and obtain responses for them effectively. Thus, this study develops a database-supported and BIM-based CMI (DBCMI) system for general contractors to enhance their CMI work efficiency during the construction phase. To confirm the efficacy of the CMI, the DBCMI system was used in a building project in Taiwan. The case study results reveal that the proposed DBCMI system is an effective communication and management platform, particularly for practical CMI work integrated with BIM technology. This study concludes with the benefits of using the proposed system and possible limitations in its further application.

1. Introduction

A construction project faces numerous interface issues emerging from various fields that must be effectively resolved to enhance construction management. To this effect, the effective communication and management of interfaces (CMI) can be an essential aspect for a project's stakeholders. General contractors must consider a suitable platform with which to exchange feedback and responses related to construction interface management. While e-mail and general construction information systems are widely used communication tools, their ability to record and manage interface problems and responses is limited. Building information modeling (BIM) technology, by contrast, can digitize and deliver information in a 3D computer-aided design (CAD) environment [1]. In the context of construction interface management, BIM technology can help project stakeholders manage and track interfaces integrated with 3D BIM illustration. Thus, BIM as an information technology (IT) can contribute toward improving the efficiency and success of a construction project [2, 3].

BIM-based information systems are currently used in construction interface management because no appropriate platform yet exists for project participants to integrate CMI work with BIM technology. Furthermore, the limitation of file-based BIM model format needs to be overcome to provide the effective illustration for construction BIM-enabled interface management. Therefore, the aim and objective of the study is to develop a database-supported and BIM-based CMI (DBCMI) system to overcome the file-based BIM model limitation and enhance the efficiency of CMI work in a web environment. This study creates a novel database-supported and BIM-based communication platform that enables project participants to discuss, share, and respond to problems and issues related to the BIM elements-based interface during the construction phase. The DBCMI system enables project engineers and project managers to access records of previous and current discussions regarding BIM models for a given project and to manage and respond to interface problems (Figure 1). The DBCMI system can also be used during the construction phase to track the most recent problems and responses to BIM-based interface issues from project engineers. We applied the DBCMI system to a Taiwan building project case study to verify the effectiveness of CMI applications. This study presents the findings, suggestions, benefits, and limitations of the DBCMI system for further practical implementation.

2. Literature Review

The interfaces should be identified and managed effectively for all the participants involved to minimize deleterious changes during the construction phase of the project [4–6]. Only limited research has examined interface management issues in construction. Al-Hammad proposed 19 common interface problems identified based on four categories (financial problems, inadequate contract, specification, and environment problems) [7]. Also, there are many research studies focusing on the frameworks and approaches special in construction interface management [6, 8–12]. There are some research studies focusing on case studies for construction practical interface management [10, 13–17]. There are some construction interface management research studies focusing on information system developments [5, 11, 18–21]. The above research studies focus mostly on the interface management approaches and internet-based interface management system developments in construction.

BIM is a digital tool that supports continual updating and sharing of project design information [22]. BIM is a process of creating and using digital models for design, construction, and/or operations of projects [23]. Eastman et al. described the BIM as tools, processes, and technologies that are facilitated by digital or machine-readable documentation about a building [1]. BIM is a process focusing on the development, use, and transfer of a digital information model of a building project to improve the design, construction, and operations of a project or portfolio of facilities [24]. BIM provided a digital technology for describing and displaying information required in the planning, design, construction, and operation of constructed facilities [25].

During the construction phase, there are many information system developments integrated with BIM technologies. Ku and Mahabaleshwarkar presented the concept of building interactive modeling (BIM) which complements with BIM technology to enhance collaborative information and knowledge sharing [26]. Chen and Luo explored and discussed the advantages of 4D BIM for a quality application based on construction codes integrated with product, organization, and process (POP) data definition structure [27]. Lin applied BIM concepts and approaches to enhance the construction interface management implementation [21]. Han and Golparvar-Fard leveraged 4D BIM and 3D point cloud for monitoring construction progress deviations at the operational level [28]. Matthews et al. proposed a new object-oriented workflow and processes for progress management integrated with cloud-based technology during construction [29]. Costin et al. utilized RFID-BIM integration to generate real-time data to produce leading indicators for building protocol control [30]. Lin et al. proposed a BIM-based defect management (BIMDM) system for on-site quality management during the construction phase [31]. Fang et al. integrated BIM and RFID technologies to provide cloud-enabled RFID indoor localization solution [32]. Park and Cai developed WBS-based dynamic multidimensional BIM database for total construction as-built documentation [33]. Hamledari et al. developed to automatically update schedule and progress system using BIM technology and industry foundation classes (IFC) during construction [34].

Numerous information systems have been developed for various purposes; however, few studies have focused on system development in the context of construction interface management integrated with BIM technology. There is a lack of suitable platforms for BIM-based CMI work based on literature reviews. Moreover, the limitation of traditional file-based BIM model format needs to be overcome in sharing and visualizing the latest construction progress [35]. To solve this problem and overcome the limitation of file-based BIM practices for interface management, this study develops web-based DBCMI system to enhance CMI work efficient. Especially, the proposed approach and system proposed in the study differ from other existing BIM software and BIM-related information system development.

3. Research Method

From interviews with senior project managers and engineers experts in Taiwan's construction industry, the study obtained the following major problems relating to interface management experienced by general contractors [36]: (1) no suitable platforms or functions are available to support the interface management of CMI work, (2) the records of communication and responses regarding interfaces are insufficient and incomplete, and (3) it is unclear whether the problems are caused by problem parts in the construction project.

To overcome these problems, the proposed system needs to incorporate the following: (1) full integration of CMI work with the construction projects and activities, (2) records of the communications and responses for each interface issue for CMI work, and (3) links between the contents of CMI work with the elements of the BIM models used in the project.

The study proposes the concept of BIM-based interface management for GC during construction (see Figure 2). There are three proposed statuses for CMI work in the study. They are pending confirmation status, continued discussion

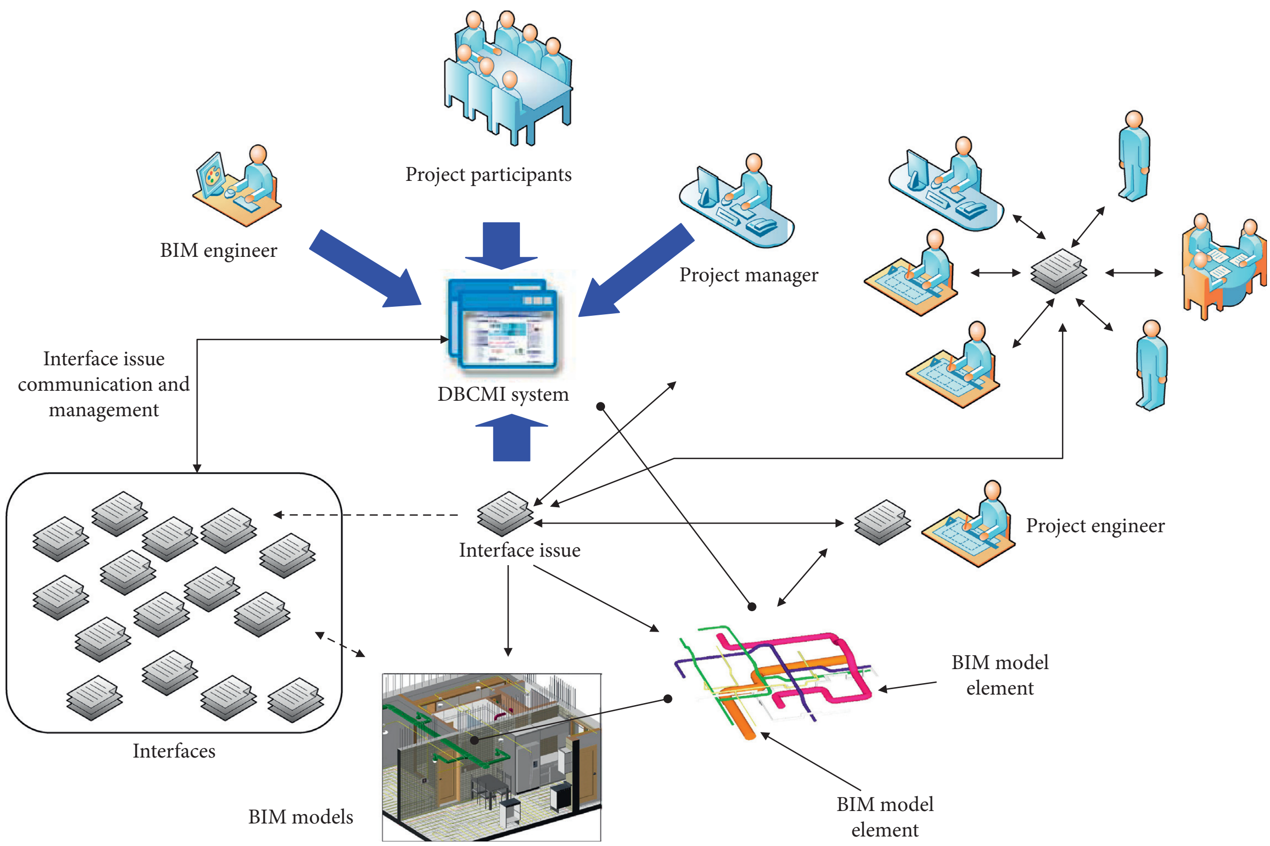


Figure 1: The application of DBCMI system for construction interface management.

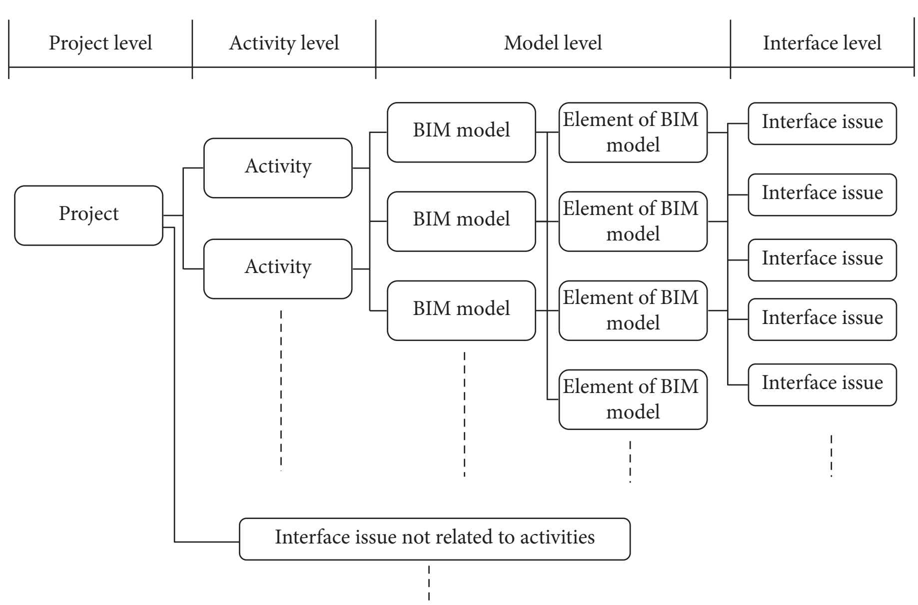


Figure 2: The concept of BIM-based interface management for GC during construction.

status, and completed discussion status (see Table 1). In order to help project engineers and project managers to access and manage interface problems integrated with elements of BIM models, this study proposes interface breakdown structure (IBS) and model breakdown structure (MBS) approach integrated with BIM. An interface breakdown structure (IBS) in interface management is a deliverable-oriented breakdown of a project into related interfaces (elements). IBS is an hierarchical representation of interfaces, starting from higher levels and going down to finer level interfaces (elements). This is similar to the approach of the Work Breakdown Structure (WBS). Furthermore, a model breakdown structure (MBS) in

Table 1: Description of CMI status in case study.

Status	Description
Pending confirmation	Proposed interface is awaiting the project manager's confirmation prior to the initiation of a discussion
Continued discussion	Ongoing discussion with related engineers or awaiting responses to a project manager's confirmation
Completed discussion	Final phase of discussion and confirmation received from the project manager

interface management is a deliverable-oriented breakdown of a BIM model into smaller elements of BIM models for interface management. A model breakdown structure is a key interface integrated with elements of BIM models. Figure 3 shows the framework of database- and BIM-based interfaces communication and management integrated with IBS and MBS. Figure 4 illustrates the preprocessing of BIM models for CMI work.

The CMI-related information stored in elements of BIM model includes both CMI-related problems and solutions. The major information for CMI should include topic of interface, description of interface, response of interface, or related attachments (e.g., documents, reports, drawings, and photographs). CMI-related problems and solutions in the BIM-based communication and respond are associated with projects, activities, people, and organizations. Identifying the relationships between interfaces and all CMI-related information are essential for project managers and project engineers when tracking and managing interfaces in the project. Additionally, the most recent CMI-related problems and solutions can be acquired from project engineers and then shared and linked with corresponding BIM model elements for interface management and future reference. The DBCMI system is a web-based platform that utilizes 3D BIM model illustration with different levels of access to CMI work that depends on user roles. When information is updated in the DBCMI system, the server automatically sends e-mails to the related project participants associated with the interface issue.

There are three stages for CMI work in the study. In the initial stage, the responsible participants or project managers identify all interface issues. In the second stage, the project participants edit the interface issues, select an appropriate BIM model and its elements, and link the interface problems associated with the BIM model's elements. These may include accounts of unconfirmed interface issue problems, detailed situation information, and solutions to problems. In the final stage, the engineer submits the interface issues associated with the BIM model elements to the DBCMI system for approval. After obtaining approval from the project manager, responsible participants respond to problems via the selected interface in the DBCMI system. The system tracks the most recent status and shows the result for each interface problem. Participants can directly access the related interface issues and mark up the comments by linking the BIM model elements. The following section describes the development of the proposed DBCMI system.

4. System Implementation

The DBCMI system is developed and executed in Microsoft Windows Server 2010 for use by the project manager, project engineers, the BIM manager, and BIM engineers. This study uses the BIM model as a visual tool for the interfaces. The BIM model elements are broken down and entered into the database of DBCMI system in advance. These elements are linked with the interface information in the DBCMI system for interface management using API programming. The proposed DBCMI system enables participants to access the related interface information and records through the database-supported elements of the BIM models, which were developed for this study using Autodesk Revit and Trimble Tekla Structure.

Interface issue information integrated with the BIM elements in the BIM models was achieved using application programming interface (API) and Microsoft Visual Basic .Net (VB.Net) programming language. Furthermore, WebGL technology is utilized to display BIM models and elements of the BIM models in the web environment in the study. Figure 5 shows the framework of the DBCMI system. Figure 6 presents the system and modules of the DBCMI system. Figure 7 illustrates the system process flow chart used in the DBCMI system.

The DBCMI system utilizes a three-tier architecture to integrate the database-supported elements with the BIM models' illustration. This improves and enhances the BIM-based interface management. The three distinct tiers are the database layer, the application layer, and the presentation layer, which are described in the following.

The database layer comprises two databases on the server side: the BIM-CMI database and the BIM elements database. The BIM-CMI database stores and maintains all communication records regarding interface issues, and the BIM elements database stores all information related to the BIM model elements. The two databases are associated with a unique ID linked to the main index by a primary key. The unique ID is required for retrieving complete interface information from the two databases to perform data associations needed for data mapping for CMI work. A firewall protects the system database from intrusion.

The application layer integrates and utilizes BIM software for various applications required for indexing, updating and transferring data/information, visualizing the status, and generating reports. When the application programming interface (API) modules in the DBCMI system receive a request from the client, the application layer can acquire and analyze the data based on the request and present the results to the client side.

The presentation layer, the main illustration platform of the DBCMI system, enables the project manager and project engineer to access and edit the interface communication records and the responses to topics associated with the BIM model elements via a PC or tablet (client side) for CMI implementation.

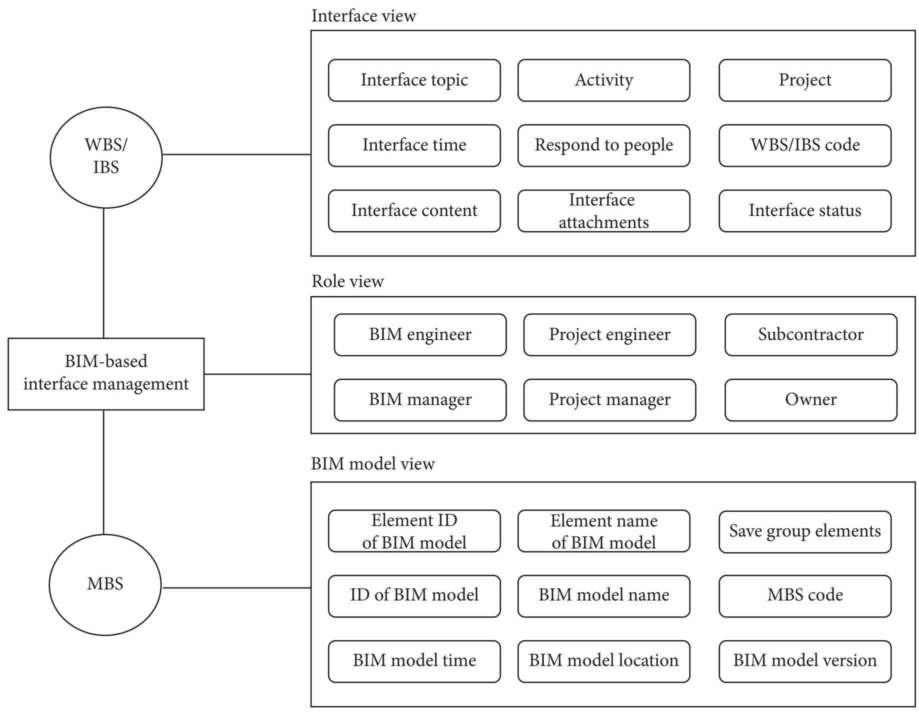


Figure 3: The framework of database- and BIM-based interfaces communication and management.

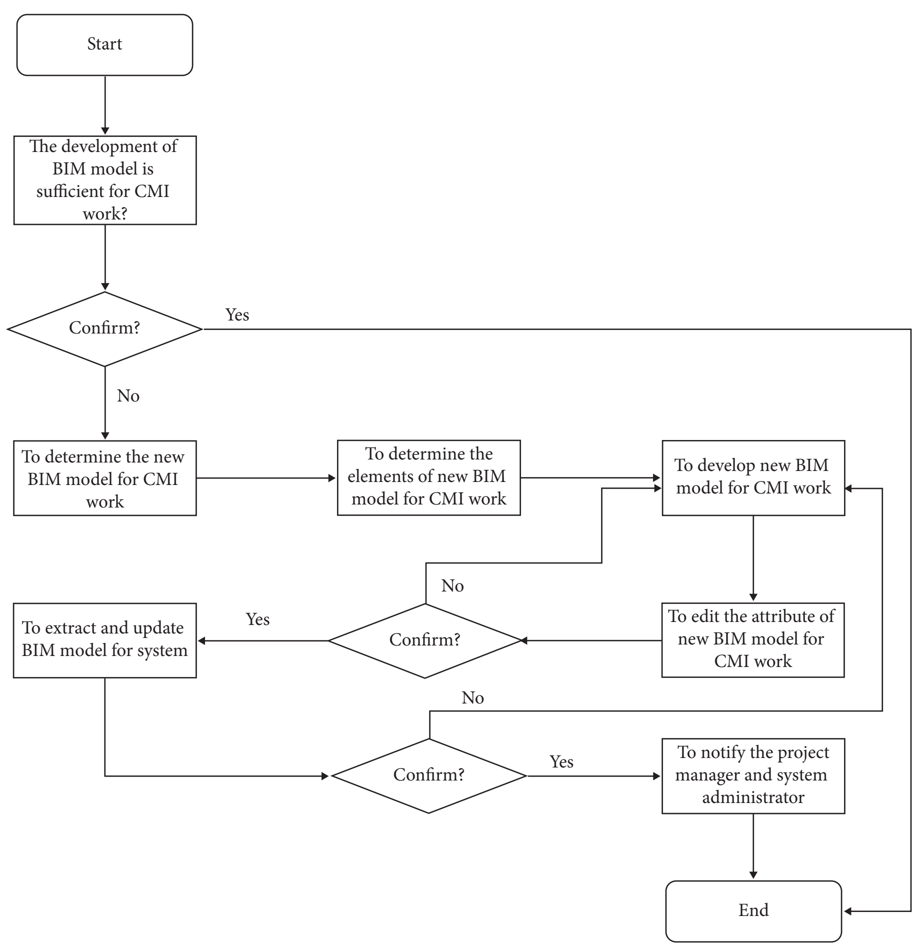


Figure 4: The preprocessing of BIM models for CMI work.

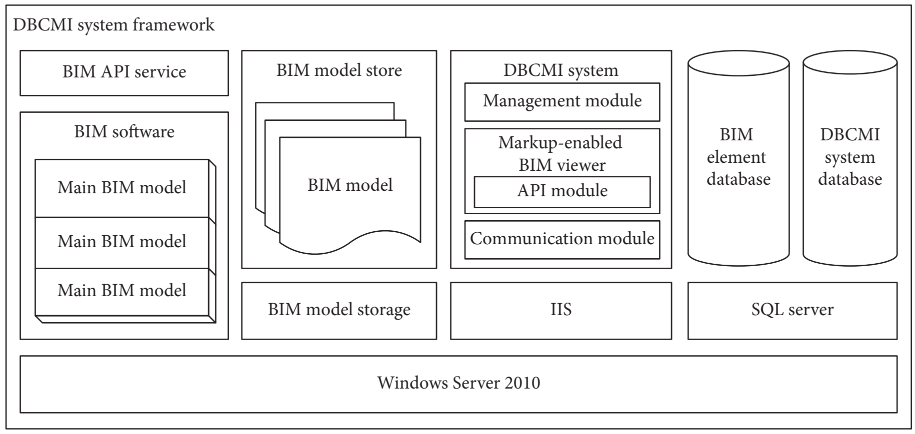


Figure 5: System framework of the DBCMI System.

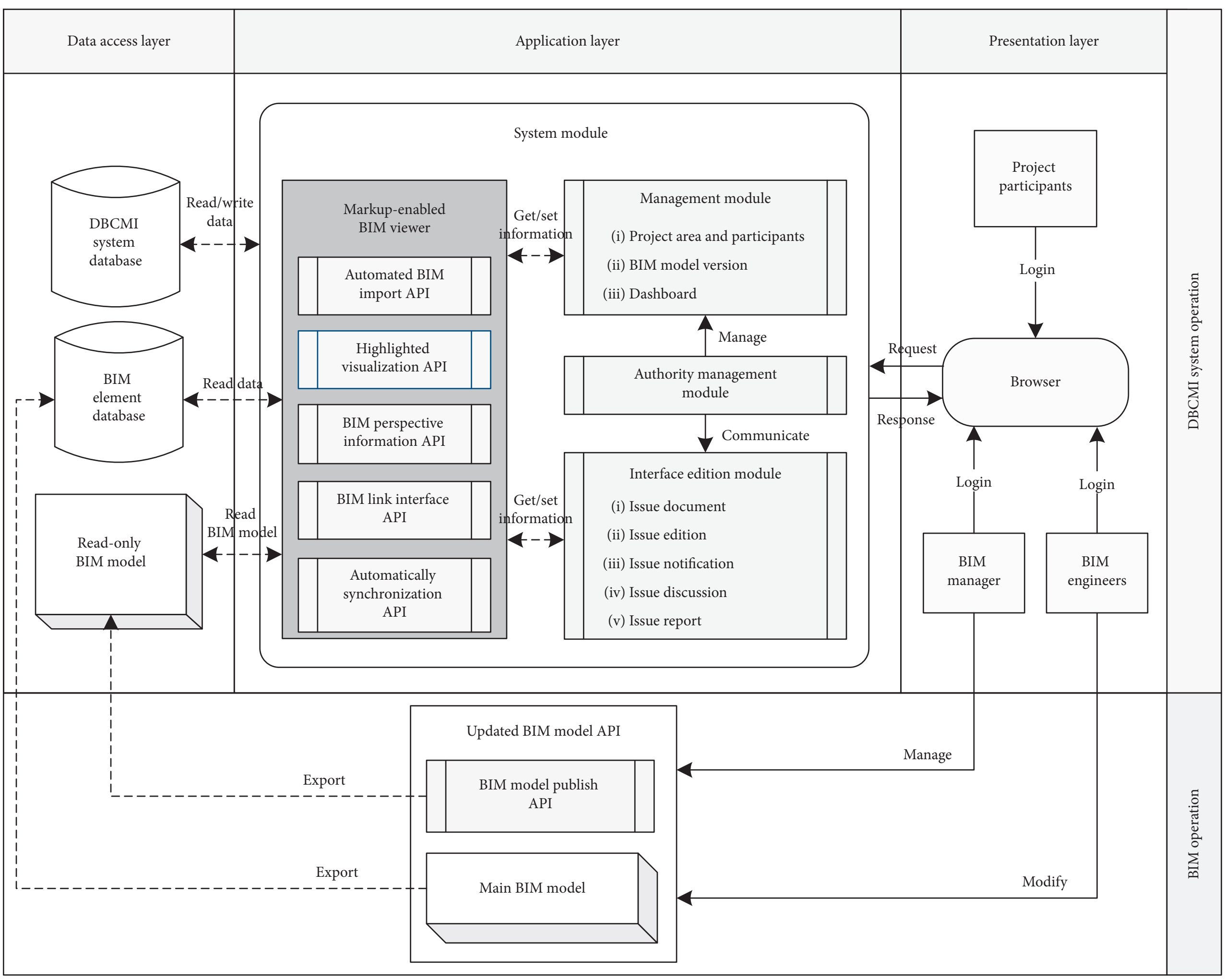


Figure 6: System and modules of the DBCMI system.

This study develops a novel markup-enabled BIM viewer integrated with WebGL technology to enhance and track interfaces of markup information linkage with the elements of BIM models efficiently during the CMI work process. The markup-enabled BIM viewer can be defined as a 3D CAD graphic representation of interface issues linking relationships between BIM objects and attributes of interfaces. The markup-enabled BIM viewer, which is defined in multiple objects, is constructed from variables that can be decomposed into elements of BIM model to store the identified problems of CMI work. The markup-enabled BIM viewer allows users to access CMI-related problems stored in layers based on

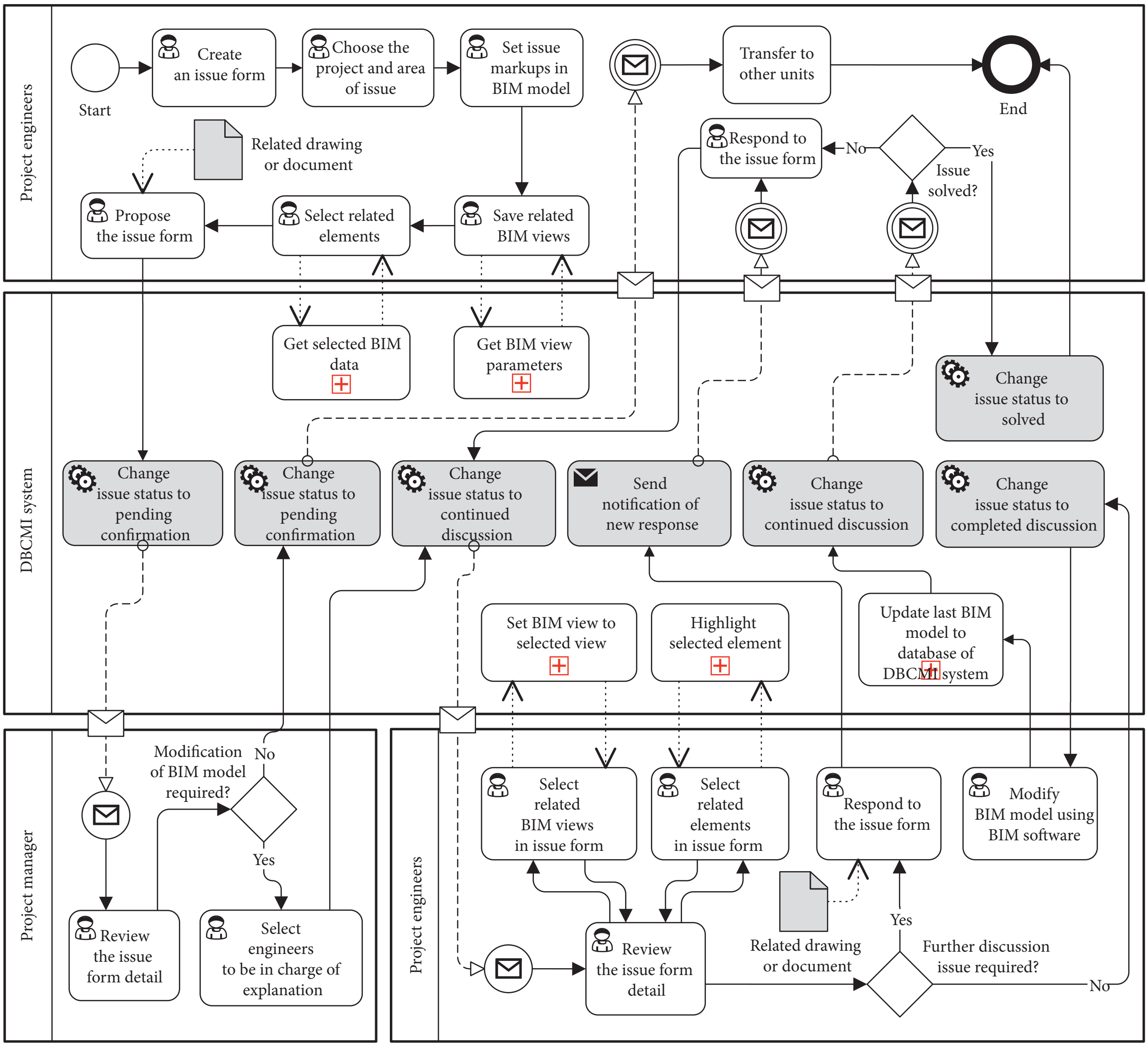


Figure 7: The system process flow chart used in the DBCMI system.

interface problem. Only authorized participants can access the markup-enabled BIM viewer for interface issue information entry and update based on their responsibilities in the DBCMI system. The BIM approach retains digital interface information and enhances CMI-related discussion and communication in the BIM environment. The markup-enabled BIM model elements are designed to be easily integrated with interfaces and elements of BIM models. Assisted by the 3D BIM approach, CMI-related problems in the markup-enabled BIM viewer can be identified and managed effectively during the process.

The following section demonstrates the implementation functionalities of the DBCMI system.

4.1. Authority Management Module. The proposed module includes an access control mechanism that prevents unauthorized users from accessing sensitive information. Only registered project participants have access to the DBCMI system, and access rights and authorities vary for different project participants.

4.2. Interface Edition Module. This module provides an environment for project participants to edit interface information (or attached files), select elements of BIM models, and communicate with each other in a similar way to instant messaging, enabling users to exchange comments online. Project participants can post questions, responses, and comments, thereby generating records of discussions regarding particular topics.

4.3. Search Module. To enable project participants to search the interface quickly and easily, the search module offers indexing, full text search, element ID search, and location/area search functions.

To integrate the system with the elements of BIM model, the DBCMI system incorporates the following six API programming modules.

4.4. Automated BIM Import API Module. This module improves the effectiveness of importing BIM elements into the editing format by automating the process. Users can directly edit the interfaces of the BIM models.

4.5. Highlighted Visualization API Module. This module uses bright colors to highlight relevant elements of the BIM model, providing the user with swift and effective access to the relevant interface.

4.6. BIM Link Interface API Module. This module links the two databases through an element ID index. This data association can be used to retrieve complete information and records of interfaces for data mapping.

4.7. BIM Perspective Information API Module. This module allows the project participants to save their current view of the BIM model (i.e., view position, direction, elevation, distance, and zoom information) so that other project participants can access the same view to get a clear understanding of the interface and BIM model elements.

4.8. Automatic Synchronization API Module. This module enables users to access the latest BIM model elements in the system. To maintain an accurate and efficient system performance, the module automatically synchronizes updated BIM model element information.

4.9. Dashboard API Module. This module enables users to access the latest interface status and information directly through the dashboard. To improve the tracking and management performance for CMI work, the module automatically synchronizes the newest updates to interfaces in the dashboard.

The BIM engineer is responsible for creating the BIM models, breaking the BIM model down into elements, and saving them in the BIM elements database prior to commencing CMI work operations. The BIM engineer also updates and resynchronizes the BIM elements database when the content of the BIM models is changed or revised. Finally, Figure 8 illustrates comparison of CMI work process in the current practice and the proposed DBCMI system.

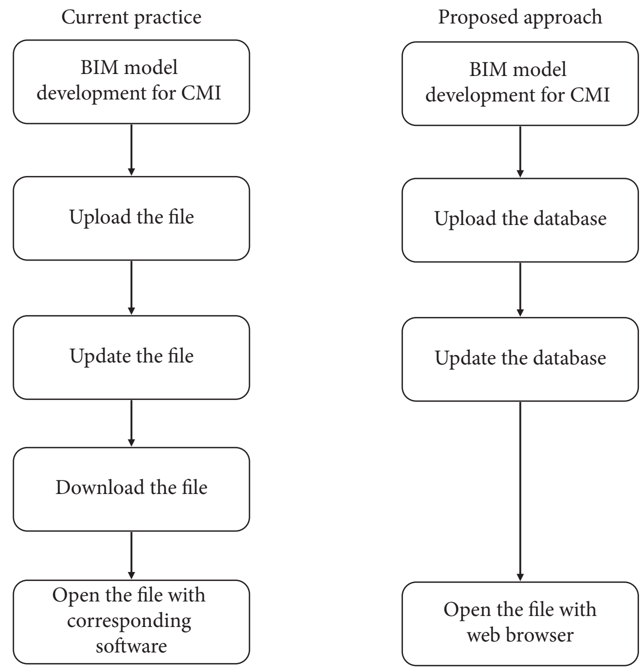


Figure 8: Comparison of CMI work process in the current practice and the proposed approach.

5. Pilot Case Study

5.1. Pilot Case Description. This section presents a pilot study demonstrating BIM implementation to manage construction interfaces in Taiwan. The case includes a general contractor who has 28 years of experience and intends to adopt BIM to enhance construction interface management for a 13-month commercial building project with approximately 2,350 activities. The project comprises three underground and 16 above-ground floors. The general contractor has previously adopted BIM for interface management but believes that the models are not free from certain limitations. Consequently, the contractor utilized the DBCMI system to communicate and manage interfaces and verify its effectiveness for CMI.

We asked all participating engineers to evaluate the DBCMI system and conducted a field test by first inviting participants to discuss the possible issues faced while using the DBCMI system. Here, we present the case of an interior decoration engineer in charge of door installation on the first floor of the project. Prior to installation, the engineer was required to undertake certain prework and thus used the system to enter and edit related interface information for interface management. Next, the engineer selected interior-related elements in the BIM model using the markup-enabled BIM viewer and edited the associated WBS, IBS, and MBS codes. Upon entering the information and attaching the related files, the engineer assigned two on-site engineers to the issue on the DBCMI system. Once this request was confirmed by the project manager, the pending status changed and the selected participants were notified via e-mail.

As the DBCMI system reflected a continued discussion status, one of the two responsible on-site engineers received an automated e-mail notification and was required to respond to the related interface issue. To do so, the on-site engineer selected the interface issue, accessed the door installation elements in the concerned BIM model, and reviewed the content (Figure 9). The on-site engineer identified possible delays in the schedule owing to specific reasons and accordingly the system highlighted in red the impacted elements of the BIM model for door installation to indicate the delay (Figure 10). The on-site engineer then submitted the issue along with the necessary explanation. Once the issue was updated in the system, both the interior decoration engineer and the other on-site engineer were e-mailed an update.

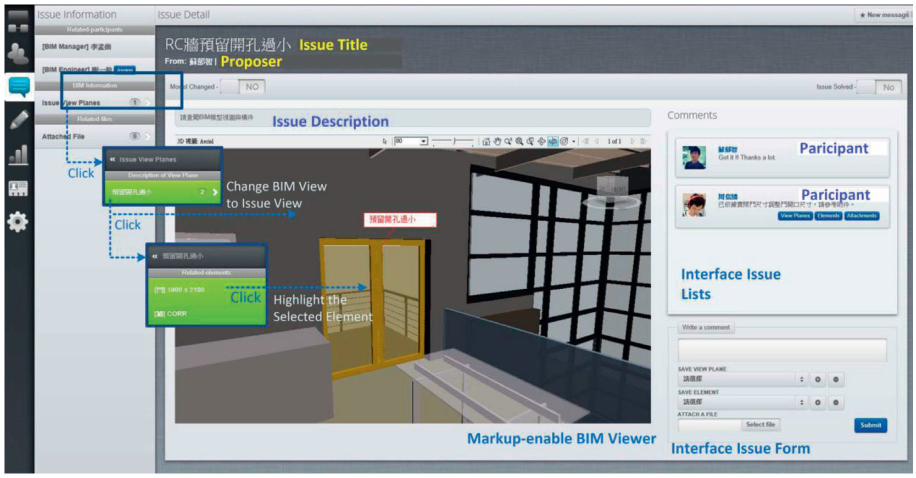


Figure 9: The interface-sharing using the DBCMI system in case study.

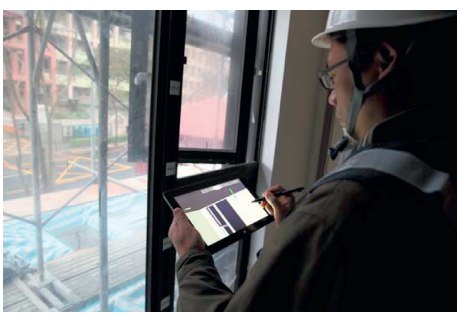


Figure 10: On-site engineer accessed and responded interface contents using the DBCMI system at construction site in case study.

The interior decoration engineer then proposed the closure of the interface discussion and waited for the project manager to confirm this action. Once the project manager confirmed the closure, the DBCMI system updated the issue with a completed discussion status. All authorized participants were notified of this update via e-mail.

5.2. Field Tests and Results. Prior to conducting the field experiment, we installed the DBCMI system on the general contractor's main server. Participants in the project were asked to use the DBCMI system for CMI work. We performed tests to verify if the system operated in line with the specified tasks and validated system utility. As part of the tests, the participants—including two project managers with 20 years of experience, six senior project engineers with 10 years of experience, five junior project engineers with two years of experience, and three BIM engineers with four years of experience—were asked to provide feedback via questionnaire. The questionnaires focused on evaluating system function and determining user satisfaction with system capabilities. Then, we asked the users to compare the system with previous approaches and grade its usage, functionality, and capability on a five-point Likert scale, where 1 denotes "not useful" and 5 is "very useful." In addition, we asked the participants to offer recommendations for possible improvements to the DBCMI system. We observed that the majority of participants used the DBCMI system for BIM. Table 2 shows the results for the tests and Tables 3 and 4 list the project engineers and project managers' evaluation comments.

Below are our major findings for the DBCMI system and its benefits. First, 85% of respondents agreed that the system facilitated their access and referral to BIM-related interface information that was integrated with BIM model elements. Second, 86% of respondents could use the system to collaborate with other stakeholders and share interfaces related to the BIM elements in the 3D BIM models. Finally, 90% of respondents stated that the DBCMI system facilitated effective communication and management in a web-based BIM environment.

However, the respondents also highlighted certain limitations. First, the number of updates of content stored on the DBCMI system was insufficient to complete CMI work. Second, modifying and updating the BIM models was time consuming and the BIM engineers needed considerable assistance. Unfortunately, certain participants were unwilling to provide feedback on interface updates and related procedures.

The respondents offered the following recommendations on the basis of their system usage. First, project managers and engineers should be allowed sufficient time to edit and respond to BIM-related CMI information. Second, support from the senior management regarding system implementation is imperative to ensure successful utilization of the DBCMI system. Third, project engineers should be sufficiently trained to review the BIM models using the markup-enabled BIM viewer. Finally, the results from the initial case study should be used in user education regarding the BIM software and emphasizing the need for training.

In sum, the case study highlights that senior management support is essential to successfully implement and adopt BIM on-site. In this case study, the job site manager extended complete support to incorporate the DBCMI system and encouraged project engineers to use the BIM model and DBCMI system for CMI work to communicate BIM-related interface issues. In addition, when utilizing

Table 2: System evaluation results.

	Standard deviation	Average rating
System usage		
Ease of interface communication	0.63	4.64
User interface	0.52	4.65
Willingness to use system for interface communication	0.53	4.32
Ease of use	0.63	4.64
System capability		
Reduces rework	0.47	4.71
Easy of finding BIM-based CMI information	0.52	4.23
Improves BIM-based CMI problems and results tracking	0.47	4.71
Reduces BIM-based CMI communication rework	0.52	4.50
Enhances BIM-based CMI response records	0.43	4.62
Reduces BIM-based interface issues sharing problems	0.52	4.50
Illustrates and understand BIM-based interfaces clearly	0.43	4.23
Enhances BIM-based interface illustrations using BIM model elements	0.41	4.76
Improves BIM-based complete records for CMI work	0.42	4.53

Note. The mean score is calculated on the basis of the participants' rating on a five-point Likert scale, where 1 = "strongly disagree" and 5 = "strongly agree."

Table 3: Project engineers' evaluation comments.

No.	Participant comments
1	The proposed DBCMI system integrated with the markup-enabled BIM viewer is very useful in handling identified interface problems with related BIM model elements.
2	The DBCMI system saves considerable time (almost one-third) when handling interface problems and responses (e.g., reentry of information) and helps me to communicate and resolve interface issues at the job site effectively.
3	I can use the DBCMI system to respond to current interface problems (or discussions) and easily access unfinished interface results.
4	The system helps me to understand all interface problems, explanations, and illustrations through the BIM models easily and quickly.
5	The DBCMI system is very effective in the CMI process and allows me to communicate the BIM model elements related to the interface issues with the engineers.
6	The biggest advantage of DBCMI is that it records all communication regarding the BIM model elements. This is helpful when I need to refer back to necessary information about the elements.
7	The DBCMI system is very effective for interface management integrated with BIM. I can access the system via the Internet to read interface information.
8	The case study does not cover all interface issues regarding the BIM models. Therefore, there are likely to be problems in the practical application of BIM technologies for interface management.
9	While the practical application is subject to many limitations, the DBCMI system can enhance the performance of interface communication.
10	I previously used e-mail to check and track the latest inspection results and modification work for the final as-built model. With the proposed markup-enabled BIM viewer under the DBCMI system, I can now do the same more quickly and effectively. The system significantly helps project engineers to communicate and discuss interfaces and improves the decision-making process.

BIM as a communication tool for CMI work, it is necessary to update the model to its latest version.

6. Conclusions

The BIM approach has been one of the most promising developments in the architecture, engineering, and construction (AEC) industry in recent times. The CMI work can be integrated with BIM technology to assist stakeholders such as project managers, project engineers, and BIM engineers in the construction phase of their projects. This study thus proposes a novel database-supported BIM-based CMI system integrated with elements of the BIM model to enhance CMI work. The DBCMI system allows project participants to manage and respond to all interfaces via a web environment integrated with WebGL technology.

The academic and practical literature suggests numerous BIM-based system developments related to construction interface management; however, the majority of the BIM-based systems for CMI work are file based. A key characteristic of the proposed DBCMI system is its ability to overcome the limitations of file-based BIM models, thus enabling more effective visualization and sharing for BIM-based interface management during the project construction phase. In addition, we introduce IBS and MBS approaches to integrate BIM and interface management. This solution can improve the visualization of interface discussions and management among project participants. In particular, it helps effectively integrate discourse in the BIM model and improve the communication of information when interfaces are related to BIM model elements. Further, the API modules used in the DBCMI system are designed and developed with a simplified user interface and operations to increase the willingness of participants to use the system, especially among participants who are unfamiliar with BIM software.

In this study, we verify the effectiveness of the proposed DBCMI system for CMI work by applying it to a Taiwanese building project. The results of the case study reveal that the system allows participants to identify, track, coordinate, and manage interfaces that are integrated in the database-supported elements of the BIM models. The field experiment results further support that the proposed system with BIM and WebGL technology provides an effective, user-friendly platform for construction interface management.

Table 4: Project managers' evaluation comments.

No.	Participant comments
1	Generally, using screen captures of BIM models and communicating interface discussions with related engineers can be time consuming. The system is a helpful communication platform for BIM models integrated with illustrations on the web that saves much time when communicating interfaces.
2	The DBCMI system helps me to manage current interface results and track all ongoing interfaces effectively. The system is more convenient and helpful than e-mail.
3	The DBCMI system provided me with easy access to related interfaces and information and it helps communicate and handle interface problems and responses.
4	I previously used e-mail to check and track interface issue results and work. However, with the DBCMI system, I can trace and manage the same more quickly and effectively. In fact, the system is very useful for project engineers and managers when handling interface problems and responses.
5	The DBCMI system records all communication regarding the BIM model elements, which is very helpful when I need to refer to related information. Also, the DBCMI system's functions differ from those of existing BIM tools and software.
6	It took me a while to learn the DBCMI system. In the beginning, it was not easy and I needed other engineers' assistance to use the system. However, I am now used to managing and responding to interface issues using the system.
7	One of the problems I faced before using the DBCMI system was not being able to understand the mistakes identified and illustrated by the BIM models. The DBCMI system helps me to understand all problems, explanations, and illustrations regarding construction interface issues more easily.
8	The proposed markup-enabled BIM viewer in the DBCMI system could significantly enhance interface discussions and responses and applies an effective view of construction interface management.

This study makes the following major contributions. First, we introduce IBS and MBS approaches integrating BIM and interface management. Second, we develop a novel markup-enabled BIM viewer using API to simplify BIM-based interface management. Finally, the database-supported DBCMI system overcomes the limitations associated with using traditional file-based BIM models for CMI work.

Going forward, construction interface management can be improved and integrated with innovative technology. For example, BIM can be integrated with augmented reality (AR) and virtual reality (VR) technology to visualize construction interface management effectively by general contractors during the construction phase.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge the Ministry of Science and Technology, Taiwan, for financially supporting this work under contract no. MOST-107-2221-E-027-024 and express their appreciation to all involved project participants for their assistance in the system design and development.

References

[1] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owner, Managers, Designers, Engineers and Contractors*, John Wiley & Sons, Hoboken, NJ, USA, 2nd edition, 2011.

[2] H. Rivard, "A survey on the impact of information technology in the Canadian architecture, engineering and construction industry," *Journal of Information Technology in Construction (ITcon)*, vol. 5, no. 3, pp. 37–56, 2000.

[3] Y. H. Ahn, Y. H. Kwak, and S. J. Suk, ""Contractors' transformation strategies for adopting building information modeling," *Journal of Management in Engineering*, vol. 32, no. 1, pp. 1–13, 2016.

[4] G. N. Evans, A. Bailey, M. Reed et al., "Organising for improved construction interfaces," *Innovation in Civil and Construction Engineering*, vol. 49, pp. 207–212, 1997.

[5] Y. C. Lin, "Construction network-based interface management system," *Automation in Construction*, vol. 30, pp. 228–241, 2012.

[6] S. Shokri, S. Ahn, S. Lee, C. T. Haas, and R. C. G. Haas, "Current status of interface management in construction: drivers and effects of systematic interface management," *Journal of Construction Engineering and Management*, vol. 142, no. 2, article 04015070, 2015.

[7] A.-M. Al-Hammad, "Common interface problems among various construction parties," *Journal of Performance of Constructed Facilities*, vol. 14, no. 2, pp. 71–74, 2000.

[8] D. K. H. Chua, A. Tyagi, S. Ling, and S. H. Bok, "Process-parameter-interface model for design management," *Journal of Construction Engineering and Management*, vol. 129, no. 6, pp. 653–663, 2003.

[9] D. K. Chua and M. Godinot, "Use of a WBS matrix to improve interface management in projects," *Journal of Construction Engineering and Management*, vol. 132, no. 1, pp. 67–79, 2006.

[10] Q. Chen, G. Reichard, and Y. Beliveau, "Interface management–a facilitator of lean construction and agile project management," in *Proceedings of Fifteenth Annual Conference of the International Group for Lean Construction (IGLC-15)*, pp. 57–66, East Lansing, MI, USA, July 2007.

[11] Q. Chen, G. Reichard, and Y. Beliveau, "Object model framework for interface modeling and IT-oriented interface management," *Journal of Construction Engineering and Management*, vol. 136, no. 2, pp. 87–198, 2010.

[12] W. Shen, W. Tang, S. Wang, C. F. Duffield, F. K. P. Hui, and R. You, "Enhancing trust-based interface management in international engineering-procurement-construction projects," *Journal of Construction Engineering and Management*, vol. 143, no. 9, article 04017061, 2017.

[13] W. T. Chan, C. Chen, J. I. Messner, and D. K. Chua, "Interface management for China's build-operate-transfer projects," *Journal of Construction Engineering and Management*, vol. 131, no. 6, pp. 645–655, 2005.

[14] V. Senthilkumar and K. Varghese, "Case study–based testing of design interface management system," *Journal of Management in Engineering*, vol. 29, no. 3, pp. 279–288, 2012.

[15] S. Shokri, C. T. G. Haas, R. C. Haas, and S. H. Lee, "Interface-management process for managing risks in complex capital projects," *Journal of Construction Engineering and Management*, vol. 142, no. 2, article 04015069, 2015.

[16] S. Ahn, S. Shokri, S. Lee, C. T. Haas, and R. C. Haas, "Exploratory study on the effectiveness of interface-management practices in dealing with project complexity in large-scale engineering and construction projects," *Journal of Management in Engineering*, vol. 33, no. 2, article 04016039, 2016.

[17] H.-H. Yeh, T.-Y. Hsieh, and J.-H. Chen, "Managing complex engineering interfaces of urban mass rapid transit projects," *Journal of Construction Engineering and Management*, vol. 143, no. 6, article 05017001, 2017.

[18] T. C. Pavitt and A. G. F. Gibb, "Interface management within construction: in particular, building facade," *Journal of Construction Engineering and Management*, vol. 129, no. 1, pp. 8–15, 2003.

[19] V. Senthilkumar, K. Varghese, and A. Chandran, "A web-based system for design interface management of construction projects," *Automation in Construction*, vol. 19, no. 2, pp. 197–212, 2010.

[20] F.-C. Siao and Y.-C. Lin, "Enhancing construction interface management using multilevel interface matrix approach," *Journal of Civil Engineering and Management*, vol. 18, no. 1, pp. 133–144, 2012.

[21] Y.-C. Lin, "Use of BIM approach to enhance construction interface management: a case study," *Journal of Civil Engineering and Management*, vol. 21, no. 2, pp. 201–217, 2015.

[22] F. Gould and N. Joyce, *Construction Project Management*, Prentice-Hall, Bergen, NJ, USA, 3rd edition, 2008.

[23] N. W. Young, S. A. Jones, H. M. Bernstein, and J. E. Gudgel, *SmartMarket Report: The Business Value of BIM: Getting Building Information Modeling to the Bottom Line*, McGraw-Hill Construction, New York, NY, USA, 2009.

[24] J. Messner, C. Anumba, C. Dubler et al., *BIM Project Execution Planning Guide Version 2.1, The Computer Integrated Construction Research Program (CIC)*, Penn State University, State College, PA, USA, 2011, http://bim.psu.edu/.

[25] ISO Standard, *ISO 29481-1:2016(E): Building Information Modeling—Information Delivery Manual—Part 1: Methodology and Format*, ISO, Geneva, Switzerland, 2nd edition, 2016, https://www.iso.org/standard/60553.html.

[26] K. Ku and P. S. Mahabaleshwarkar, "Building interactive modeling for construction education in virtual worlds," *Journal of Information Technology in Construction (ITcon)*, vol. 16, no. 13, pp. 189–208, 2011.

[27] L. J. Chen and H. Luo, "A BIM-based construction quality management model and its applications," *Automation in Construction*, vol. 46, pp. 15–23, 2014.

[28] K. K. Han and M. Golparvar-Fard, "Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs," *Automation in Construction*, vol. 53, pp. 44–57, 2015.

[29] J. Matthews, P. E. D. Love, S. Heinemann, R. Chandler, C. Rumsey, and O. Olatunj, "Real time progress management: Re-engineering processes for cloud-based BIM in construction," *Automation in Construction*, vol. 58, pp. 38–47, 2015.

[30] A. M. Costin, J. Teizer, and B. Schoner, "RFID and BIM-enabled worker location tracking to support real-time building protocol and data visualization," *Journal of Information Technology in Construction (ITcon)*, vol. 20, no. 29, pp. 495–517, 2015.

[31] Y.-C. Lin, J.-X. Chang, and Y.-C. Su, "Developing construction defect management system using BIM technology in quality inspection," *Journal of Civil Engineering and Management*, vol. 22, no. 7, pp. 903–914, 2016.

[32] Y. Fang, Y. K. Cho, S. Zhang, and E. Perez, "Case study of BIM and cloud-enabled real-time RFID indoor localization for construction management applications," *Journal of Construction Engineering and Management*, vol. 142, no. 7, article 05016003, 2016.

[33] J. Park and H. Cai, "WBS-based dynamic multi-dimensional BIM database for total construction as-built documentation," *Automation in Construction*, vol. 77, pp. 15–23, 2017.

[34] H. Hamledari, B. McCabe, S. Davari, and A. Shahi, "Automated schedule and progress updating of IFC-based 4D BIMs," *Journal of Computing in Civil Engineering*, vol. 31, no. 4, article 04017012, 2017.

[35] J. Park, H. Cai, P. S. Dunston, and H. Ghasemkhani, "Database-supported and web-based visualization for daily 4D BIM," *Journal of Construction Engineering and Management*, vol. 143, no. 10, pp. 1–12, 2017.

[36] Y. C. Lin, "The study of BIM-assistant interface management for GC during construction," The Report for BIM Interface Management Implementation in Construction, Taiwan, 2013.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 8547928, 12 pages
https://doi.org/10.1155/2019/8547928

Research Article

Augmented Reality for Identifying Maintainability Concerns during Design

Imad A. Khalek, Jad M. Chalhoub, and Steven K. Ayer

Arizona State University, School of Sustainable Engineering and the Built Environment, 660 S College Ave, Tempe, AZ 85281, USA

Correspondence should be addressed to Imad A. Khalek; iabdulkh@asu.edu

Received 30 November 2018; Revised 23 January 2019; Accepted 12 February 2019; Published 3 March 2019

Guest Editor: Eugenio Pellicer

In a building context, decisions made early in the design phase can have a major impact on maintainability of the resulting facility. Effectively leveraging the knowledge of facility management teams in the design stage can lead to improved maintainability in the operation phase, but this feedback can be challenging to elicit during the design stage because facility management teams may not be formed by the time of design. This requires designers, who may not have facility management experience, to think like facility managers in order to consider the needs of the maintenance teams. This paper examines the extent to which different visualization media may be able to enable individuals without prior maintenance experience to identify maintainability concerns in a design model. Student participants, without prior maintenance experience, were randomly assigned to explore a design to assess maintainability concerns with either augmented reality (AR) or a traditional computer screen for viewing a Building Information Model (BIM). Their perceptions, behaviors, and statements were recorded and analyzed. Results indicate that BIM supports better identification of potentially problematic areas, but AR allows users to more consistently determine why an area is problematic. This suggests an opportunity to use a hybrid BIM/AR approach for identifying and resolving maintainability considerations during the design phase. The findings from this work provide evidence to illustrate how AR and BIM may enable individuals with limited experience to be able to effectively think like facility managers in order to make better maintainability decisions during design to lead to a better building during operation.

1. Introduction

Maintainability, defined as restoring a component to its initial original design state [1], is essential for the long-term functionality of any building [2]. Maintainability can greatly impact the Life Cycle Cost (LCC) and functionality of a facility [3, 4], attributing to between 50% and 80% of a project's total cost [5, 6]. However, maintenance resources are continually decreasing while costs continue to increase [7], and facility managers (FMs) are facing an increasing frequency of design-related maintainability issues [8]. Improving maintenance processes is essential for the long-term success of any project.

The leading cause of operation and maintenance issues in facilities is the lack of maintainability considerations in the design phase, despite designers' best efforts [9]. Although designers attempt to make the best decisions possible, most operational problems in a facility are largely attributed to decisions made in the design phase [10]. For example, air handler vents need to be opened to change filters on a regular basis. If these units do not have sufficient clearance for the vent to be opened, changing filters will be difficult or impossible. This example illustrates the type of impact that design decisions can have on maintainability. Considering maintainability in design decisions can lead to more sustainable and cost-effective facilities during operation [11, 12].

One possible strategy to produce more maintainable facilities is to include FMs in the design phase [13]. While this can provide substantial value when executed correctly, researchers report potential problems with communication between FMs and designers [14]. Furthermore, communication between FMs and designers is uncommon among industry teams [15]. This is partly due to the fact that facility management teams are frequently not formed by the time of design, making it impossible to get their input [16]. Challenges in communication between designers and FM teams can contribute to inadvertent downstream problems resulting from early project decisions.

Augmented Reality (AR) is a visualization technology that overlays virtual objects onto the real world [17]. The use of AR by designers to view models during design review sessions allows them to physically interact with virtual design concepts at full scale, similar to how they would actually interact with the physical building. This suggests a theoretical opportunity for AR to enable designers to better identify maintainability concerns by mimicking FM practices in maintainability-focused design review sessions, through the physical interactions afforded with AR.

In recent years, construction professionals have been getting more involved in the design phases of projects. In fact, BIM adoption among contractors is higher than among designers [18]. While this suggests BIM experience among construction companies, experienced construction professionals are diminishing due to the present labor shortage in North America [19]. This may illustrate the need for less-experienced individuals to be able to effectively leverage BIM and related technologies to provide critical input during design. This study aims to determine the extent to which individuals with limited construction experience are able to provide effective input using AR and more traditional BIM visualization formats when participating in maintainability-focused design review sessions.

This paper answers the following questions: What behaviors related to designing for maintainability are enabled while reviewing an existing design through AR as compared to Building Information Models (BIMs) through a traditional computer screen? How does reviewing the design using AR impact the recognition and evaluation of maintainability issues compared to BIM? These questions are addressed using an experimental procedure comparing the behaviors and performances of participants using AR and traditional BIM during maintainability design review sessions. The subsequent sections detail the research approach and findings.

2. Background

2.1. Designing for Maintainability. Maintainability is largely impacted by design decisions, and these decisions often lead to inadvertent consequences during the operation of a facility [20]. The lack of maintainability considerations in the design phase is further evident when considering FMs' increasing costs [21]. A number of factors, such as accessibility, cleaning, and replacing components, and determination of parts are all affected by decisions made in the design phase [22]. These previous findings highlight the opportunity to improve the current design process in order to create more maintainable buildings.

Most areas that prove to be difficult to maintain are directly related to a lack of maintainability considerations in design [23, 24]. Checklists have been introduced to guide designers to create more maintainable designs in general [25] and also for specific systems [26]. Having a series of checklists to consider for each component may lead to cognitive overload while designing may lead to over-designing [27]. Methods to include maintainability considerations in design have been developed, but application of such methodology has proven to be difficult.

In response to the challenges associated with following detailed design checklists, other publications have suggested general maintainability criteria for design professionals to consider. For example, designers should ensure enough space to allow access and reach to components [12], reduce the general complexity of systems included [28], make the design more easily adjustable in the future if needed [29], and utilize longer-lasting components [12]. Despite advancements in designing for maintainability, maintenance problems due to building designs persist [9].

2.2. Building Information Modeling. Building Information Modeling (BIM) involves the development of virtual representations of buildings with physical and functional features [30]. This includes information such as precise geometry, cost estimates, material inventories, and project schedule to which all participants refer throughout the process of design, construction, operation, and maintenance [30]. While BIM use has been increasing during design [31] and construction stages [32], researchers are just beginning to realize its benefits in the operations and maintenance stage [33]. BIM has been used to aid in developing maintenance plans, in order for maintenance personnel to locate and assess the location of work orders in facilities [34]. Kumar and Cheng studied the use of BIM to optimize space utilization and travel time in facilities [35]. Wetzel and Thabet developed a BIM-based framework to increase FMs' safety while attending to maintenance repairs [36]. Another effort used BIM and Construction Operations Building Information Exchange (COBIE) to aid with preventative maintenance for facilities [37]. Love proposed a learning mechanism to aid FMs in recognizing the value of BIM and its benefits in facility maintenance [38]. These studies illustrate the potential for BIM to offer value in operation and maintenance phases.

However, fewer studies have incorporated BIM in the design phase for FM purposes [39]. Wang illustrated the potential for BIM to support design for FM by enabling pathway optimization, energy management, and commissioning [40]. Despite this potential, viewing virtual BIM content for maintainability concerns can also be challenging, and maintainability issues can easily be hidden within the model [41]. These studies illustrate the potential for BIM to elicit early design feedback that can support operational needs, but it is not yet clear the extent to which BIM environments may effectively enable designers to think like end-users to identify problematic design elements in existing construction projects.

2.3. Augmented Reality. Augmented Reality (AR) is a technology that enables virtual objects to be overlaid onto the physical world, allowing the user to view them as if they were real [42]. AR has been shown to offer potential value in different stages of a construction project [43]. In pre-construction, an AR-based construction planning tool was tested instead of using 2D plans to reduce construction planning errors [44]. During construction, participants using AR were observed to be significantly faster in assembling electrical conduit than those using 2D plans, and they had fewer errors [45]. Yeh et al. studied AR for on-site information retrieval, in order to view construction drawing specifications instantly instead of using 2D plans [46]. AR was also used for equipment operation modeling to maintain safe and effective construction practices [47]. These studies illustrate how AR may support various performance gains related to construction tasks.

In addition to construction applications, researchers have also found merits to using AR technology in various maintenance and maintainability tasks. Zhou discussed the feasibility of using AR to rapidly inspect segment displacement during tunneling construction [48]. Lee utilized an AR interface that monitors real-time construction operation data of equipment to maintain efficiency on-site [49]. Other work demonstrated the use of an AR tool for FMs to access additional information that they may need while undergoing regular facility repairs and inspections [50]. AR has also been used for maintainability by assisting mechanics in removing and installing components, plugs, and fasteners in the manufactured product industry [51]. Schall et al. presented an AR system for aiding field workers of utility companies in outdoor maintenance tasks [52]. While AR is being increasingly utilized for maintenance during the operation phase, little effort has been made to assess the value of using AR to enhance maintainability considerations of the different components during the design phase. This paper addresses this knowledge gap.

3. Methodology

To study the behaviors of individuals with limited facility management experience when using AR and BIM during maintainability design review sessions, the researchers identified existing maintainability issues and developed a 3D model that aggregated those areas into a single space. The researchers then used an experimental methodology to compare students' abilities to identify design concerns in the same model when visualizing that content either with AR or with BIM on a traditional computer screen. Figure 1 provides an overview of the research methodology followed. The subsequent sections detail the procedure followed by the researchers.

3.1. Identifying Common Maintainability Issues. The researchers collaborated with the facility management team of a large university to identify the most common maintainability issues encountered in built facilities that could have potentially been avoided with different design decisions. The researchers toured multiple facilities at the university, accompanied by the FM personnel responsible for maintaining each facility. The researchers noted and photographed the areas that the FMs considered challenging or impossible to maintain due to specific attributes of the design. Subsequently, interviews were conducted to determine the frequency of these problems in other facilities. Accessibility was the main cause of maintainability concerns, and four different types of maintainability issues were identified, as summarized in Table 1.

Theoretically, these recurring types of accessibility problems should be detected during maintainability-focused design review sessions. However, as evidenced by the frequency of observing these issues in practice, these issues are often missed during design, which lead to instances of unmaintainable building designs. Therefore, this research aims to study the extent to which AR enables less-experienced individuals to recognize critical maintainability concerns that are frequently missed in the current design process.

3.2. Model Development. A 5-meter by 5-meter equipment room model was developed by the researchers for the purposes of this experiment. In the model, three types of maintainable elements were included: ball valves, push/pull valves, and air vents. Twelve total elements were included. Six of these incorporated maintainability problems that were reported by the FM team and the other six represented acceptable design scenarios. Of the six problematic areas, three corresponded to obstruction issues, and one corresponded to horizontal reach, vertical reach, and other ergonomic restrictions, respectively. The researchers chose to include more obstruction issues in order to more accurately represent the frequency of maintainability concerns, as reported by the FMs during prior interviews and site walks. After developing the model, it was shown to FMs, and they confirmed that the maintainable areas were in fact maintainable and that the nonmaintainable areas were in fact problematic. This process helped to validate that the building elements deemed to be problematic and not problematic were accurately categorized, according to current professionals. The resultant model is shown from two viewpoints in Figure 2.

All 12 valves and vents were numbered with unique identification numbers (IDs) to enable participants to clearly state which element they were viewing. The numbered IDs were not in any particular order and were not numbered one through 12 to avoid participants from being able to discern how many elements they should be seeing within the model. Designers would not know how many problematic elements they should be seeking during a model review, so the researchers intentionally did not tell participants how many they should be expecting either.

3.3. Developing AR Application. After finalizing the model content, the authors began building the AR application. Theoretically, the authors could have elected to use virtual reality (VR) instead of AR, but VR does not intrinsically allow a user to be able to see his or her own body in the visualization experience. Instead, this may simulated through the use of an avatar. While it is possible that VR may

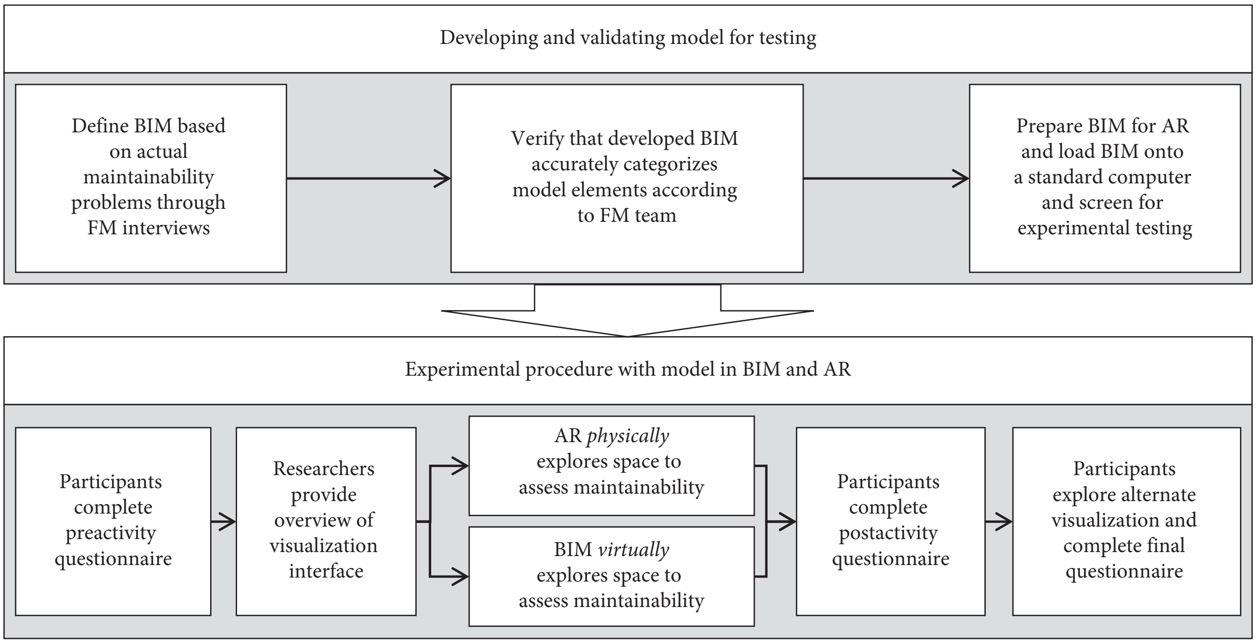


Figure 1: Model development and methodological approach followed by researchers.

Table 1: Accessibility categories and their definitions.

Categories	Definition
Horizontal reach	Areas that are difficult to reach on a horizontal axis, not intended to include instances where standard equipment would allow a FM sufficient access
Vertical reach	Areas that are difficult to reach on a vertical axis, not intended to include instances where standard equipment would allow a FM sufficient access
Obstruction	Areas that include components that block other components' range of motion during maintenance
Other ergonomic restrictions	These areas may result in FMs having limited maneuverability while maintaining the component

provide value to a maintainability-focused design review, the authors strategically targeted the unique physical engagement affordances of AR. This enabled them to determine the extent to which participants would physically experiment in the environment to perform the types of tasks that eventual FMs would be expected to perform and observe how that interaction may support the generation of relevant design for maintainability feedback.

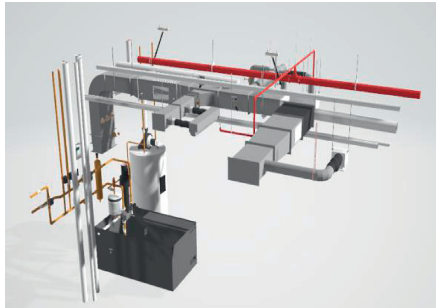
For this work, the authors elected to use the Microsoft HoloLens, which is a head-mounted display (HMD) that allows users to visualize the design at 1 : 1 scale. This device uses infrared sensors to map users' surroundings and allows them to interact with virtual content overlaid onto their view. Furthermore, this HMD does not require a physical connection to a computer, which enables users to move freely in space.

The model was exported from the native BIM software to a FBX file, which was in turn imported into the Unity Game Engine for development for the intended AR device. Scripts were added in Unity to add control to the model. Four voice-based commands were integrated: "Higher," "Lower," "Reset," and "Stop." "Higher" moves the model downward to simulate the user going slowly upward, and "Lower" moves the model upward to simulate the user moving down. These functions were added to allow users to simulate the change in elevation and accessibility enabled by using a ladder. To allow users to choose their own desired elevation for exploration, a "Stop" function would stop model movement when this word was spoken. Finally, "Reset" enables the user to recalibrate the model into its initial position on the ground floor automatically. These commands allowed the participants to interact with the AR space in a safe manner, but also allowed them to view the space similarly to how a real FM might interact with the physical space.

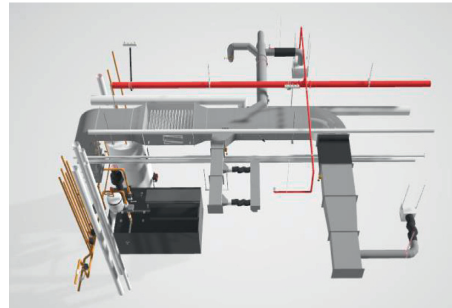
3.4. Experiment Activity. Participants were recruited from a senior construction management class at Arizona State University. The participants had at least two internships each and reflected the less-experienced target audience of this paper. The following sections detail the steps taken by participants throughout the experiment.

3.4.1. Preexperiment. The participants were first given a consent form to permit their data to be used for research, in accordance with the authors' Institutional Review Board. Participants were then asked to fill a prequestionnaire. The questions involved in this work are included in Table 2.

After participants completed the questionnaires, they watched a video presentation that introduced the activity to them. During this video, the valves and vents included in the model were shown, and the function of each was



(a)



(b)

FIGURE 2: 3D model used in both visualization methods.

TABLE 2: Prequestionnaire questions.

Prequestionnaire questions (and response options)
(1) Have you been a part of a design review session before? (Yes/No)
(2) Have you been a part of a design review session that assessed maintainability before? (Yes/No)
(3) Do you have any experience in facility maintenance? (Yes/No)
(4) If you answered "yes" to the previous question, please specify your role and responsibilities during your experience. (Short answer)
(5) Do you have any experience using AR? (Yes/No)

demonstrated. For example, the way to open and close specific valves was shown. Additionally, the four categories of accessibility in Table 1 were explained to the participants. This helped to ensure that each participant understood what type of model element he or she was expected to locate and also that each participant could differentiate between the access concern categories that were defined.

Before starting the design review activity, a think-aloud protocol was also introduced to the participants. Participants were specifically asked to state what they were thinking throughout the activity. As participants identified numbered building elements, they were asked to state the number of the area they were exploring and then state whether the area was maintainable or not. If participants stated that a modeled element was not maintainable, they were asked to choose the accessibility category that they felt described the nature of the issue. If any participant did not state clear and complete information about a particular modeled element that they were exploring, the researcher intervened to ask for additional information as required. This protocol helped to illustrate the underlying thought processes performed by the student participants.

3.4.2. During Experiment. Each participant was randomly assigned to complete his or her design review using either Navisworks on a traditional computer screen or using the developed AR content. The BIM and AR models used the exact same model file (FBX format), which was exported from commonly used BIM software. This ensured that the specific content viewed by all participants was identical and only the format of that visualization changed. If the participant was assigned to the computer screen, the "walk", "zoom," and "orbit" commands in Navisworks were demonstrated. If the participant was assigned to use AR, he or she was assisted in wearing the headset, taught the four voice commands, and instructed on how to physically navigate the space to move in the virtual model. Figure 3 illustrates what the experimental space and user experience involved in this work. In both AR and BIM cases, the experiment began when the participant stated that he or she understood how to navigate the model.

Each participant was asked to navigate the virtual space in order to locate areas that included one of the numbered components (i.e., ball valves, push/pull valves, and air vents) in the real space, as illustrated in Figure 3. It was also made clear to the participants to discontinue the activity immediately if they felt any discomfort or dizziness. After locating one of these components, the participant stated the information required from the think-aloud protocol. The entire design review experiment was video- and audio-recorded, which allowed for subsequent analysis of results by the researchers.

3.4.3. Postdesign Review Activity and Alternative Visualization. After completing the activity using either visualization format, participants were provided with a post-questionnaire. The content of the questionnaire is included in Table 3.

When participants completed the questionnaire, they were shown the alternative visualization tool. If they originally viewed the model in AR, they were shown the model on a computer screen and vice versa. The participants were asked to briefly look through the model and consider a single instance of a valve or vent to familiarize themselves with the alternate visualization format. Based on their experiences with both visualization formats, a final questionnaire was given to the participants. The content presented in the questionnaire can be seen in Table 4.

The responses to these questions helped to illustrate the perceptions of the students regarding their preferences after they had an opportunity to explore both visualization formats.

3.5. Analysis. Three main data points were extracted from the design review activity: the number of areas that each participant found, whether each identified area was

(a) (b)

Figure 3: The space used for the augmented reality environment: third person and first person views.

Table 3: Postquestionnaire questions.

Please indicate the extent to which you agree with the following statements (0 = strongly disagree and 10 = strongly agree)
(1) It was easy to find the location of all targeted components
(2) I was able to identify which of the target elements posed a maintainability concern
(3) I provided effective suggestions to improve maintainability

Table 4: Final questionnaire questions.

Please indicate the extent to which you agree with the following statements (0 = strongly disagree and 10 = strongly agree)
(1) Augmented Reality can help users think more like facility managers
(2) I would prefer to use AR over traditional BIM in designing for maintainability
(3) AR was easier to use than BIM (on computer screen)
(4) (Choose one) If I were to conduct another design for maintainability design review session I would use:
(i) Augmented Reality (AR)
(ii) BIM (on computer screen)
(iii) AR and BIM (on computer screen)
(iv) Others

considered by the participant to be maintainable or not, and the accessibility category in which the participants placed the areas, if applicable. The data recorded during the experiment were inputted into a spreadsheet, which allowed for sorting and organizing the data points. The data points were then uploaded onto SPSS for statistical testing. The two visualization tools were compared according to their ability to allow users to locate areas and navigate the space, make effective maintainability decisions, classify problematic areas into one of the four categories, and avoid false identification of areas as nonmaintainable. False identification of an area is an instance when an area is located and reported as problematic by the participant even though it did not receive any maintainability concerns from the FMs interviewed. A representation of the analysis structure and corresponding result section is illustrated in Figure 4.

The videos collected from the design review activity were exported into behavioral coding video analysis software. The videos of the participants using AR were analyzed for two specific sets of behavior: physical interactions and verbal interactions with the model. A physical interaction with the model consisted of any movement the individual made relative to the model, such as using their arms to reach out and gauge distance between themselves and a virtual object. A verbal interaction was the use of any of the voice commands within the AR application. The data extracted from the analysis process was imported into a spreadsheet. The findings relating to performance and perception are presented in the following section.

4. Results

The students involved in this work had completed three years of academic coursework related to construction management and were in the process of completing their fourth year. Their academic program of study includes courses related to construction estimating, planning and scheduling, materials and methods, basic structural analysis, building systems, and other general education courses. Beyond their academic background, the participating students also completed at least one industry internship, with most students having completed more than this, which provided some basic industry experience; to guide their behavior, 3.2% of the sample had taken part in a maintainability-focused design review session prior to participating in this research. Only 15.9% of the sample had used AR at least once before, and 11.9% of the sample had previous experience in the facility management field. The low percentage of participants with experience in design review for maintainability and AR usage represent a novice participant sample, while participants' background and experience in construction indicate a basic understanding in the processes of designing, constructing, and operating facilities.

4.1. Performance

4.1. Performance. The two modes of visualization were compared according to four criteria: (1) ability to locate areas that would require maintenance; (2) ability to enable users to make decisions about whether the area is maintainable or not; (3) ability to correctly assess the type of accessibility issue; and (4) ability of users to avoid false identification of maintainability problems. Given the categorical nature of the independent variables, the researchers used cross-tabs and corresponding Pearson chi-square tests to identify statistically significant relationships between the visualization medium and criteria of concern. The following subsections detail the findings in each criterion.

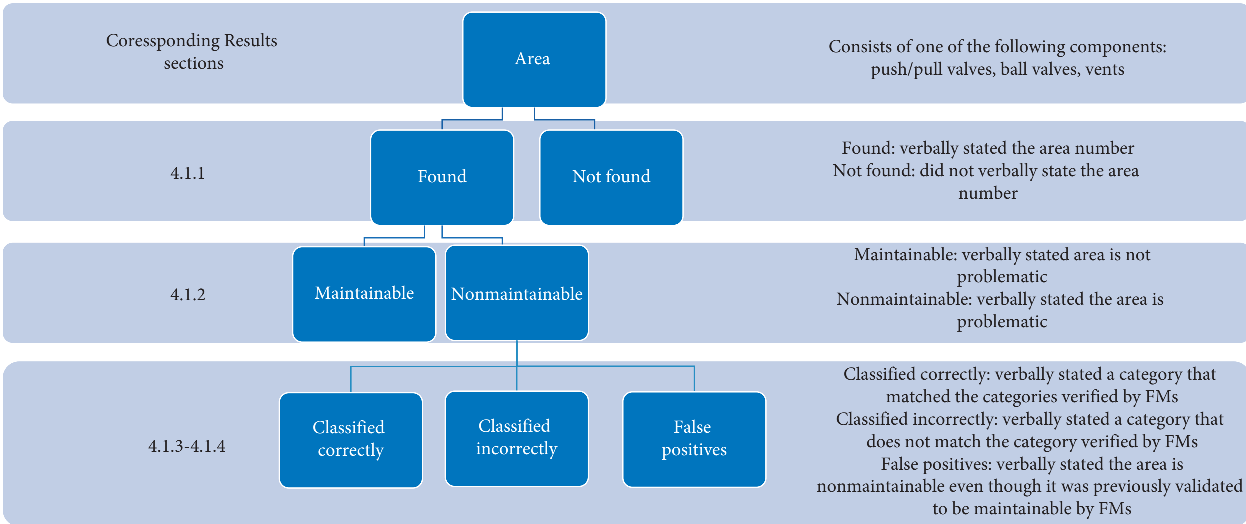


Figure 4: Steps for analyzing design review session.

4.1.1. Effect of Visualization Medium on Locating Areas. An area is considered to be located when the participant verbally states the selected area's number. Table 5 shows the number of areas and percentage found using each visualization medium.

When using BIM, the participants found 81.6% of the numbered areas in space, compared to 73.7% of the areas when using AR, and the difference is statistically significant according to the chi-squared test (P value <0.05). This indicates that users are significantly better at finding areas of interest in space using BIM on a traditional computer screen compared to when using AR.

This finding may be explained by the differences afforded through BIM and AR navigation. While the participant has to physically walk through the space when using AR to see it in its entirety, he or she can quickly pan and zoom through a BIM on a computer screen to achieve the same functionality, making space exploration significantly easier on a computer screen. This may explain the comparative ease of identifying targeted building elements in BIM over AR.

4.1.2. Effect of Visualization Medium on Identifying If Areas Are Accessible. After locating the points, the participants were asked to decide if the area they had identified was maintainable. Areas that had maintainability issues were considered correctly identified when participants verbally stated that an area was unmaintainable. Areas that did not have maintainability issues were considered to be correctly identified when participants stated that the area was maintainable. Table 6 shows the number of areas identified correctly in each medium.

When a point was found, it was correctly identified 82.4% of the time when using BIM on a screen, compared to 84.3% of the time when compared to AR. While this illustrates a numerical difference, there was not sufficient evidence to indicate a statistical difference between these performance findings according to the Pearson chi-square test (P value >0.05). Therefore, this does not provide evidence that either mode of visualization is better for determining whether something is maintainable or not.

4.1.3. Effect of Visualization Medium on Identifying the Type of Accessibility Issue. If participants locate the area and decide it is unmaintainable, they are then prompted to categorize the area into one of the accessibility subcategories. The number of correctly classified points in each medium can be seen in Table 7.

When a point was correctly identified as unmaintainable, a participant was able to correctly classify the reason 80.1% of the time when using AR, compared to 73.7% of the time when using BIM on a traditional computer display, and the difference is significant at the 95% confidence level (P value <0.05).

This indicates that participants using AR were significantly better at classifying maintainability problems. This could be attributed to the physical interactions enabled by using AR, where the participant can check whether a system is placed in the correct position in reference to the real environment. This finding is especially noteworthy because it illustrates that the physical exploration afforded through AR does not only provide a novel experience, but that this experience actually impacts students' ability to evaluate why a given building component works or not more than BIM on a computer screen.

4.1.4. Effect of Visualization Medium on Avoiding False-Positive Identification. False-positive areas represent areas that were verified as being maintainable by the FMs, but were identified as being nonmaintainable by the participant during the design review activity. Participant performance in avoiding false-positives in both visualization media was analyzed.

Table 8 shows the count and percentages of false-positives identification.

Table 5: Effect of visualization medium in locating areas and corresponding chi-square results.

Medium	Count, % within medium	Locating areas		Total	Pearson chi-square P value
		Not found	Found		
BIM (on-screen)	Count	73	323	396	0.004
	% within medium	18.4%	81.6%	100.0%	
AR	Count	98	274	372	
	% within medium	26.3%	73.7%	100.0%	

Table 6: Effect of visualization medium on identifying accessibility and corresponding chi-square results.

Medium	Count, % within medium	Correct identification		Total	Pearson chi-square P value
		Incorrect	Correct		
BIM (on-screen)	Count	57	266	323	0.262
	% within medium	17.6%	82.4%	100.0%	
AR	Count	43	231	274	
	% within medium	15.7%	84.3%	100.0%	

Table 7: Effect of visualization medium on maintainability classification.

Medium	Count, % within medium	Correct classification		Total	Pearson chi-square P value
		Incorrect	Correct		
BIM (on-screen)	Count	70	196	266	0.046
	% within medium	26.3%	73.7%	100.0%	
AR	Count	46	185	231	
	% within medium	19.9%	80.1%	100.0%	

When a participant was using AR, he or she falsely identified only 11.8% of maintainable areas as unmaintainable. Conversely, when a participant was using BIM on a traditional computer screen, he or she falsely identified 24.7% of maintainable as unmaintainable. The difference is significant at the 95% confidence level. This suggests that using AR reduces the need to review correctly designed areas in a given space, further increasing the productivity of the reviewers.

Furthermore, when using AR, participants verbally and/or physically interacted with the model in 96.8% of the areas considered. In 74.2% of the cases, the participants chose to invoke verbal interactions, allowing them to safely simulate actions that would have been undertaken by the FM, such as climbing a ladder. In 90.3% of the cases, the participants physically interacted with the model (i.e., reached out to physically touch virtual building components in an attempt to mimic the types of actions that FMs would perform). This highlights the natural inclination of participants to physically interact with the model, taking further advantage of the unique opportunities enabled by this mode of visualization.

These interactions, especially the physical ones, are unique to this type of visualization and may be the reason for the enhanced performance compared to viewing the same model on a computer screen. Similar to the results on classifying building elements, this suggests that the interactions afforded in AR allow participants to more effectively evaluate design elements for maintainability.

In the prequestionnaire, each participant was asked to identify whether he or she had any experience participating in design review sessions and whether any of those sessions were specifically maintainability-focused review sessions. Furthermore, participants were asked if they had any experience in facility management or with using AR prior to this research activity. While the responses illustrated some variation in levels of experience among participants, none of these individual attributes indicated any statistically significant effects on the performance. In other words, when assessing the ability of participants to find areas in the model, correctly identify whether the areas are maintainable or not, and correctly classify areas deemed to be unmaintainable, none of the individual attributes of participants had an impact on their performance.

4.2. Perception. The participants were asked to rate their performance on a Likert scale from 1 to 10, with 10 being the highest level of agreement with the statements, after completing the activity. The questions and average response per communication medium are detailed in Table 9. The participants seem generally comfortable using both viewing media, with bias towards AR, especially when asked about the ability of identifying maintainable areas. This is especially noteworthy because it illustrates that their perception may not necessarily match their behavior. For example, students in the AR group generally reported higher perceived ability to find components, but comparatively lower ability to determine which components posed maintainability concerns, even though this finding is in opposition to the behavioral coding analyses.

Table 8: Effect of medium on false-positive identification and corresponding chi-squared results.

Medium	Count, % within medium	Correct identification		Total	Pearson chi-square P value
		Incorrect	Correct		
BIM (on-screen)	Count	37	113	150	0.0035
	% within medium	24.7%	75.3%	100.0%	
AR	Count	14	105	119	
	% within medium	11.8%	88.2%	100.0%	

Table 9: Postquestionnaire-perception results.

Statement	AR average	BIM average
It was easy to find the location of all targeted components	8.65	8.13
I was able to identify which of the target elements posed a maintainability concern	8.69	9.06
I provided effective suggestions to improve maintainability	8.32	8.13

Table 10: Alternative visualization questionnaire results.

Statement	Mean agreement (1–10)
Augmented reality can help users think more like facility managers.	9.1
I would prefer to use AR over traditional BIM in designing for maintainability	7.63
AR was easier to use than BIM (on computer screen)	7.17

After using the second visualization medium at the end of the session, the participants were given an additional questionnaire. This helped to illustrate the preference of students to use one mode of visualization over the others. Table 10 summarizes the questions and average answers of the participants. The responses were rated on a Likert scale from 1 to 10, with 10 being the highest level of agreement.

In general, the participants agreed that AR can help users think more like facility managers in designing for maintainability. In fact, when asked to choose a visualization medium that they would like to use for a design review session, 93% of the respondents stated they would use a combination of on-screen BIM and AR. Participants stated that while viewing the same area in AR in comparison to BIM, they changed their classification of the area, stating that now that they could explore the space with reference to their own bodies and the surroundings they were able to identify possible accessibility complications in the BIM. The results indicate that participants realized that they were able to conduct more accurate inspections of the areas using AR, but may have been inclined to use both visualization methods due to the navigation capabilities of BIM.

5. Discussion

AR and BIM on a computer screen both showed advantages to users' performance. BIM on a computer screen allowed users to locate components in the model more effectively, while AR enabled users to identify how or why an area posed maintainability issues more accurately than with BIM on a computer screen. Furthermore, viewing the model in an AR environment enabled the users to avoid false-positive identification more than with BIM on a computer screen. It is also noteworthy that no participant felt any discomfort or dizziness while conducting the activity. In addition to the behavioral evidence that illustrates the potential value offered by both modes of visualization, the students also reported perceived value to both formats for various reasons. Therefore, in order to capitalize on the observed behavioral affordances and perceived advantages of each visualization method, the researchers propose a hybrid visualization approach to performing maintainability-focused design review sessions. Figure 5 illustrates the steps involved in the suggested hybrid method.

First, the researchers assume a 3D model of the designed space is either developed or obtained by the review team. A user would then start by exploring the space using a traditional computer screen, locating any areas that may seem problematic. Exploring the model on a screen initially will mitigate AR's current limitations in rendering and navigating large spaces and enable the user to automatically query the model to quickly locate similar types of devices, such as valves and vents, that may present problems.

Once the areas are located, the user can then export the model to an AR viewing environment. In AR, he or she can inspect each area, leveraging the physical and verbal interactions uniquely afforded by AR. Then, he or she would identify whether each area is maintainable or not. While evidence collected in this work did not indicate a performance difference in the ability to determine whether or not elements are problematic, AR enabled users to more effectively avoid falsely identifying acceptable areas as problematic. Therefore, this approach would capitalize on the benefits observed by users of AR.

For all the areas that the user determines that are unmaintainable, he or she would classify them into one of the four categories previously defined. Classifying the unmaintainable areas may further facilitate the process of rectifying the errors by offering a descriptive explanation of the reason why the area is not maintainable. This would remove the need to speculate during the design revision phase.

Once all the unmaintainable areas are identified and classified, the user may use either an AR or a BIM environment to discuss solutions. An external stakeholder can also be added to the discussion at this point, where AR can allow him or her to explore the design by simply walking and looking around, regardless of previous experience.

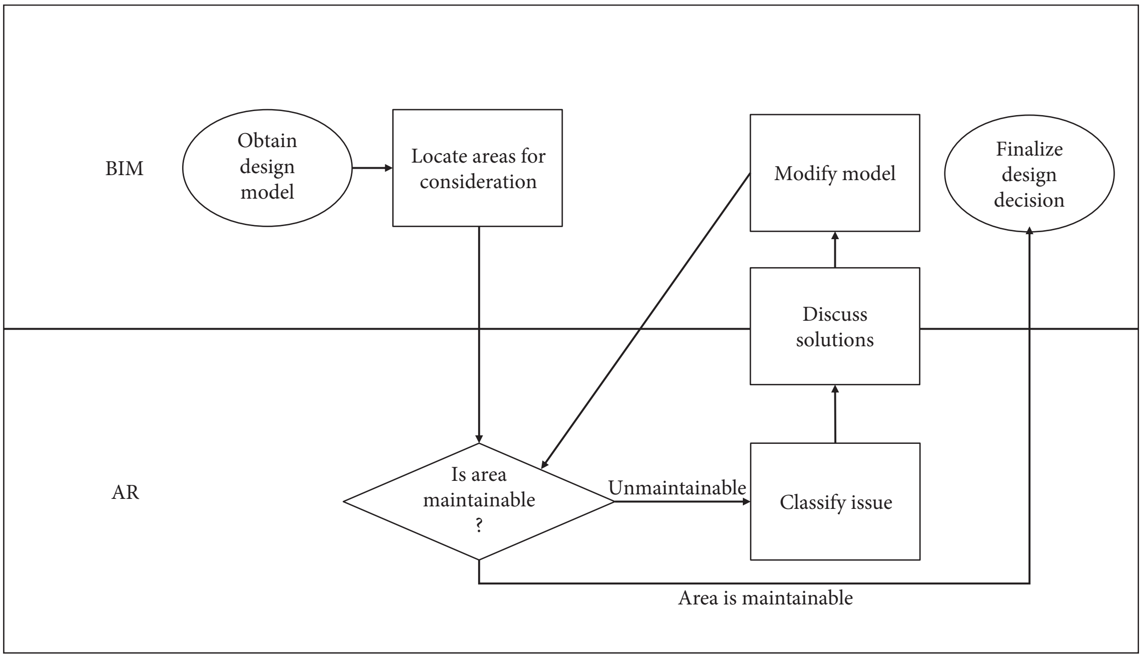


Figure 5: Hybrid visualization approach.

Once a solution is chosen, the model is rectified in a traditional BIM environment, and the model is once again exported to an AR environment, and the newly adjusted areas are checked once again for maintainability issues. This loop would continue until no maintainability issues can be found. This may be difficult to execute if the design is not adequately detailed, which is why this approach is best used during late stages of design. At that point, the model can then be finalized in a traditional BIM environment. This process provides an evidence-based approach to maintainability-focused design review sessions, but should still be independently tested to validate its effectiveness in the context of actual maintainability design reviews.

6. Limitations

There are a few limitations to the work presented in this paper related to the process and the model explored. First, during this design review session, the participants were prompted to look solely for maintainability concerns related to certain systems while exploring the space. In most actual design review sessions, designers do not focus only on maintainability of certain systems. They also consider other, nonmaintainability-related factors, such as the overall design of the room, the fit of the equipment, constructability, and other concerns depending on the type of the project. Therefore, this focus on maintainability concerns for certain building components could have impacted the ability of the participants in this work to identify maintainability concerns in design. While this may illustrate a practical limitation based on current design review practices, it also illustrates evidence to further suggest value to changing the way that maintainability reviews are conducted in order to leverage the unique affordances provided by AR and BIM when designers specifically consider the needs of FM professionals. Fully adopting this type of approach could lead to a decrease in design-related maintainability issues.

Additionally, the researchers designed the space used in this experiment by aggregating a number of areas from different existing facilities that were observed to be difficult to maintain. While both maintainable and nonmaintainable areas were included in the model, the density of the components in the overall space could potentially be higher than other equipment rooms typically reviewed in design sessions. This approach allowed the researchers to collect statistically significant samples by allowing each participant to find (or fail to find) known building components in a confined space, but it may not exactly represent the density of maintenance concerns experienced in typical design review sessions. While this should not influence the users' ability to classify components, it could theoretically allow participants in this work to locate model components more easily. This limits the extent to which authors can claim that others would find similar percentages of elements in other models; however, the proposed hybrid BIM/AR review strategy would negate this issue. If future researchers and practitioners use BIM on a computer screen to quickly identify specific building components, through automatic model queries, they could identify all points of interest regardless of model size or density. Then, they could use AR to quickly investigate the maintainability of each of the identified building components.

7. Conclusion

The researchers aimed at understanding the behaviors of individuals with limited facility management experience when using AR in comparison to on-screen BIM for maintainability-focused design review sessions. The researchers followed a comparative experimental approach, where half the participants used on-screen BIM and the other half used AR to locate areas, identify whether they are maintainable, and classify the maintainability problems using a previously defined paradigm. Participants that used BIM on a traditional computer screen were significantly more effective at locating relevant building components in space. However, by leveraging the physical interactions enabled by AR, the participants were more effective at identifying whether an area is maintainable or not and significantly more effective at classifying maintainability issues and reducing false-positive observations.

The researchers propose a hybrid visualization method for maintainability-focused design review sessions, which capitalizes on the benefits of both BIM on a traditional computer screen and AR visualizations. Using this method, a user would start by exploring the space on a computer screen to locate the areas of interest. Then, he or she would use AR to identify whether the previously located areas are maintainable and classify the maintainability problem when appropriate. Using immersive and interactive visualization approaches can enable inexperienced individuals to make more maintainable designs, especially considering the difficulties of incorporating FM input and maintainability criteria during the design phase.

The contribution of this work is in providing evidence of the differences in behaviors and decision-making observed by individuals with limited facility management experience when considering maintainability. Furthermore, this work contributes a new hybrid approach to using BIM and AR in conjunction to capitalize on the unique affordances of both technologies. These contributions will allow future researchers to target specific user behaviors related to designing for maintainability and will also allow them to implement the proposed hybrid BIM/AR strategy to make better-informed design decisions to support maintainability.

Data Availability

The data used in this research are based on observations made during an experimental procedure with human subjects. These data are protected by the Institutional Review Board (IRB) at Arizona State University (ASU) and cannot be divulged publicly. Aggregated data are shared in the manuscript to support the conclusions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study is based upon the work supported by the National Science Foundation under grant no. IIS-1566274.

References

[1] J. R. Meier and J. S. Russell, "Model process for implementing maintainability," *Journal of Construction Engineering and Management*, vol. 126, no. 6, pp. 440–450, 2000.

[2] Q. Shen, K. K. Lo, and Q. Wang, "Priority setting in maintenance management: a modified multi-attribute approach using analytic hierarchy process," *Construction Management and Economics*, vol. 16, no. 6, pp. 693–702, 1998.

[3] O. T. Femi, "Effects of faulty construction on building maintenance," *International Journal of Technology Enhancements and Emerging Engineering Research*, vol. 2, no. 3, pp. 2347–4289, 2014.

[4] P. S. Dunston and C. E. Williamson, "Incorporating maintainability in constructability review process," *Journal of Management in Engineering*, vol. 15, no. 5, pp. 56–60, 1999.

[5] S. Lee, "An extension of the technology acceptance model for BIM-based FM," in *Proceedings of Construction Research Congress 2012*, pp. 602–611, ASCE, West Lafayette, IN, USA, May 2012.

[6] B. S. Blanchard, D. Verma, and E. L. Peterson, *Maintainability: A Key to Effective Serviceability and Maintenance Management*, Wiley, Hoboken, NJ, USA, 1995.

[7] J. H. K. Lai, "Operation and maintenance budgeting for commercial buildings in Hong Kong," *Construction Management and Economics*, vol. 28, no. 4, pp. 415–427, 2010.

[8] W. K. Chong and S. P. Low, "Latent building defects: causes and design strategies to prevent them," *Journal of Performance of Constructed Facilities*, vol. 20, no. 3, pp. 213–221, 2006.

[9] N. De Silva, M. Ranasinghe, and C. R. De Silva, "Risk analysis in maintainability of high-rise buildings under tropical conditions using ensemble neural network," *Facilities*, vol. 34, no. 1-2, pp. 2–27, 2016.

[10] S. N. H. Ishak, A. H. Chohan, and A. Ramly, "Implications of design deficiency on building maintenance at post-occupational stage," *Journal of Building Appraisal*, vol. 3, no. 2, pp. 115–124, 2007.

[11] B. Wood, "Maintenance integrated design and manufacture of buildings: toward a sustainable model," *Journal of Architectural Engineering*, vol. 18, no. 2, pp. 192–197, 2012.

[12] S. Ganisen, I. S. Mohammad, L. Jawahar Nesan, A. H. Mohammed, and G. Kanniyapan, "The identification of design for maintainability imperatives to achieve cost effective building maintenance: a delphi study," *Jurnal Teknologi*, vol. 77, no. 30, 2015.

[13] J. Bröchner, "Integrated development of facilities design and services," *Journal of Performance of Constructed Facilities*, vol. 17, no. 1, pp. 19–23, 2003.

[14] D. Arditi and M. Nawakorawit, "Issues in building maintenance: property managers' perspective," *Journal of Architectural Engineering*, vol. 5, no. 4, pp. 117–132, 1999.

[15] E. Erdener, "Closure to "linking programming and design with facilities management" by eren erdener," *Journal of Performance of Constructed Facilities*, vol. 19, no. 1, p. 95, 2005.

[16] X. Meng, "Involvement of facilities management specialists in building design: United Kingdom experience," *Journal of Performance of Constructed Facilities*, vol. 27, no. 5, pp. 500–507, 2013.

[17] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," *IEICE Transactions on Information Systems*, vol. E77-D, no. 12, 1994.

[18] K. E. Cassino, H. M. Bernstein, M. A. Russo et al., *"The business value of BIM for construction in major global markets: how contractors around the world are driving innovation with Building Information Modeling"*, Smart Market Report, McGraw Hill Construction, New York, NY, USA, 2014.

[19] H. Karimi, T. R. B. Taylor, and P. M. Goodrum, "Analysis of the impact of craft labour availability on North American construction project productivity and schedule performance," *Construction Management and Economics*, vol. 35, no. 6, pp. 368–380, 2017.

[20] D. Mann, "Building maintenance management," *Journal of Building Appraisal*, vol. 3, no. 3, pp. 239-240, 2007.

[21] D. K. Ballast, *Interior Design Reference Manual: Everything You Need to Know to Pass the NCIDQ Exam*, Professional Publications Inc., Belmont, CA, USA, 5th edition, 2010.

[22] W. Lau and D. Ho, "Facilities management for building maintainability: a research framework," in *Proceedings of CIB W70 International Conference in Facilities Management*, pp. 655–670, Sao Paulo, Brazil, September 2010, https://www.irbnet.de/daten/iconda/CIB21582.pdf.

[23] A. S. Ali, K. C. Keong, N. Zakaria, U. Zolkafli, and F. Akashah, "The effect of design on maintenance for school buildings in Penang, Malaysia," *Structural Survey*, vol. 31, no. 3, pp. 194–201, 2013.

[24] S. Das, M. Y. L. Chew, and K. L. Poh, "Multi-criteria decision analysis in building maintainability using analytical hierarchy process," *Construction Management and Economics*, vol. 28, no. 10, pp. 1043–1056, 2010.

[25] I. J. Ikpo, "Maintainability indices for public building design," *Journal of Building Appraisal*, vol. 4, no. 4, pp. 321–327, 2009.

[26] M. A. Hassanain, F. Fatayer, and A. M. Al-Hammad, "Design-phase maintenance checklist for electrical systems," *Journal of Performance of Constructed Facilities*, vol. 30, no. 2, article 06015003, 2016.

[27] Z. Tjiparuro and G. Thompson, "Review of maintainability design principles and their application to conceptual design," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 218, no. 2, pp. 103–113, 2004.

[28] L. Zhu, M. Shan, and B. G. Hwang, "Overview of design for maintainability in building and construction research," *Journal of Performance of Constructed Facilities*, vol. 32, no. 1, article 04017116, 2018.

[29] N. Ismail and M. I. Mohamad, "Factors in building design that improve building maintainability in Malaysia," in *Proceedings of 31st Annual ARCOM Conference, Association of Researchers in Construction Management*, pp. 905–9014, Lincoln, UK, September 2015.

[30] BuildingSMART, *Technical Vision: OpenBIM*, BuildingSMART, Hertfordshire, UK, November 2018, https://www.buildingsmart.org/standards/technical-vision/.

[31] R. Garber, *Closing the Gap. Information Models in Contemporary Design Practice*, Wiley, Hoboken, NJ, USA, 2009.

[32] C. Merschbrock and B. E. Munkvold, "Effective digital collaboration in the construction industry-a case study of BIM deployment in a hospital construction project," *Computers in Industry*, vol. 73, pp. 1–7, 2015.

[33] Q. Lu, L. Chen, S. Lee, and X. Zhao, "Activity theory-based analysis of BIM implementation in building O&M and first response," *Automation in Construction*, vol. 85, pp. 317–332, 2018.

[34] A. Akcamete, B. Akinci, and J. H. Garrett, "Potential utilization of building information models for planning maintenance activities," in *Proceedings of the International Conference on Computing in Civil and Building Engineering*, Edited by W. Tizani, Ed., pp. 151–157, Nottingham University Press, Nottingham, UK, June 2010.

[35] S. S. Kumar and J. C. P. Cheng, "A BIM-based automated site layout planning framework for congested construction sites," *Automation in Construction*, vol. 59, pp. 24–37, 2015.

[36] E. M. Wetzel and W. Y. Thabet, "The use of a BIM-based framework to support safe facility management processes," *Automation in Construction*, vol. 60, pp. 12–24, 2015.

[37] S. Lavy and S. Jawadekar, "A case study of using BIM and COBie for facility management," *International Journal of Management*, vol. 5, pp. 13–27, 2014, http://ijfm.net/index.php/ijfm/article/view/110/114.

[38] P. E. D. Love, J. Matthews, I. Simpson, A. Hill, and O. A. Olatunji, "A benefits realization management building information modeling framework for asset owners," *Automation in Construction*, vol. 37, pp. 1–10, 2014.

[39] D. G. Cotts, K. O. Roper, and R. P. Payant, *The Facility Management Handbook*, AMACOM/American Management Association, New York, NY, USA, 2010.

[40] X. Wang, M. Truijens, L. Hou, Y. Wang, and Y. Zhou, "Integrating augmented reality with building information modeling: onsite construction process controlling for liquefied natural gas industry," *Automation in Construction*, vol. 40, pp. 96–105, 2014.

[41] R. Liu and R. R. A. Issa, "Design for maintenance accessibility using BIM tools," *Facilities*, vol. 32, no. 3-4, pp. 153–159, 2014.

[42] R. T. Azuma, "A survey of augmented reality," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4, pp. 355–385, 1997.

[43] X. Li, W. Yi, H. L. Chi, X. Wang, and A. P. C. Chan, "A critical review of virtual and augmented reality (VR/AR) applications in construction safety," *Automation in Construction*, vol. 86, pp. 150–162, 2018.

[44] X. Wang, "Using augmented reality to plan virtual construction worksite," *International Journal of Advanced Robotic Systems*, vol. 4, no. 4, p. 42, 2007.

[45] J. Chalhoub and S. K. Ayer, "Using Mixed Reality for electrical construction design communication," *Automation in Construction*, vol. 86, pp. 1–10, 2018.

[46] K. C. Yeh, M. H. Tsai, and S. C. Kang, "On-site building information retrieval by using projection-based augmented reality," *Journal of Computing in Civil Engineering*, vol. 26, no. 3, pp. 342–355, 2012.

[47] B. Kim, C. Kim, and H. Kim, "Interactive modeler for construction equipment operation using augmented reality," *Journal of Computing in Civil Engineering*, vol. 26, no. 3, pp. 331–341, 2012.

[48] Y. Zhou, H. Luo, and Y. Yang, "Implementation of augmented reality for segment displacement inspection during tunneling construction," *Automation in Construction*, vol. 82, pp. 112–121, 2017.

[49] S. Lee and Ö. Akin, "Augmented reality-based computational fieldwork support for equipment operations and maintenance," *Automation in Construction*, vol. 20, no. 4, pp. 338–352, 2011.

[50] J. Irizarry, M. Gheisari, G. Williams, and B. N. Walker, "InfoSPOT: a mobile augmented reality method for accessing building information through a situation awareness approach," *Automation in Construction*, vol. 33, pp. 11–23, 2013.

[51] C. Knopfle, J. Weidenhausen, L. Chauvigne, and I. Stock, "Template based authoring for AR based service scenarios," in *Proceedings of IEEE Virtual Reality 2005*, pp. 237–240, IEEE, Bonn, Germany, March 2005.

[52] G. Schall, E. Mendez, E. Kruijff et al., "Handheld augmented reality for underground infrastructure visualization," *Personal and Ubiquitous Computing*, vol. 13, no. 4, pp. 281–291, 2009.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 8452461, 16 pages
https://doi.org/10.1155/2019/8452461

Research Article

Methodology for Building Information Modeling (BIM) Implementation in Structural Engineering Companies (SECs)

Felipe Muñoz-La Rivera[1], **Juan Carlos Vielma**[1], **Rodrigo F. Herrera**[1,2] **and Jorge Carvallo**[1]

[1]*Escuela de Ingeniería Civil, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile*
[2]*Escuela de Ingeniería, Pontificia Universidad Católica de Chile, Santiago, Chile*

Correspondence should be addressed to Felipe Muñoz-La Rivera; felipe.munoz@pucv.cl

Received 19 September 2018; Revised 31 December 2018; Accepted 30 January 2019; Published 21 February 2019

Guest Editor: Tatjana Vilutiene

Structural engineering companies (SECs) currently have a series of deficiencies that hinder their processes and interactions, decreasing their productivity, lacking collaborative and interconnected processes, not including current work methodologies such as building information modeling (BIM). The BIM methodology seeks to integrate processes and professionals involved in engineering tasks by working on platforms with coordinated and intelligent 3D virtual models. BIM has great potential for structural engineering companies (SEC) and solves their most salient problems. This paper defines a methodology to implement BIM in the SEC, focused on solving the complexities of the design phase, those that make the implementation of BIM in these offices a nontrivial task. Characterized by the optimization of resources, flexibility, and adaptability, the methodology proposed for BIM implementation within SEC clearly and objectively identifies the resources and expectations of the organizations, sets out the requirements necessary to develop the BIM methodology, and provides practical and technical recommendations for planning and monitoring the implementation.

1. Introduction

In a building or infrastructure project, the structural design, materialized in the analysis, design, and documentation of structures is a complex and dynamic process that undergoes constant modifications and restrictions during the life-cycle of the project on the orders of the client, the architect, and/or contributions from other professionals [1]. In structural engineering companies (SECs), interactions between both professionals within and outside the organization and the workflows tend to situations that decrease productivity, interaction problems among different professionals, inefficient delivery of information, and inadequate communication channels, reworks, and recurrent changes, among others [2].

Building information modeling (BIM) is one of the most important and promising changes in the architecture, engineering, and construction (AEC) industries, as it represents a paradigm shift in the conception and gestation of projects, allowing for the development of a detailed virtual model for the different phases of a project life-cycle. Improving collaboration and harmony and achieving higher levels of efficiency, BIM allows integration in the AEC industry, which is usually characterized by fragmentation [1]. Currently, with complex and large engineering projects, these methodologies and technologies are enabling the management and processing of the generated data [2–4].

The structural design phase represents one of the most complex and dynamic tasks in the life-cycle of a project, given that structural behavior must be rigorously analyzed in adherence to a series of regulatory provisions, not to mention professional practices. This significance makes the structural design phase an essential component of the generation of the BIM model [5]. In addition, modern architectural designs increasingly include complex geometric configurations of buildings [6], which make structural analysis of buildings more complex [7]. Notwithstanding the above, there is still not a unanimously accepted method for information transfer at the structural design stage, and so it continues to be the weak link in BIM model workflows [8]. It is therefore essential to be able to solve this latter barrier and efficiently incorporate structural area processes into the work chain of typical projects, taking advantage of the fact that the success of BIM depends, to a large extent, on the efficient exchange of information generated by different disciplines [9]. BIM implementation within a structural engineering company is not a trivial task, as it represents a complete evolution of the way the work process develops [10].

The main goal of this document is to revise and provide a solution to the current problems within traditional industry standards, developing a methodology for BIM implementation in structural engineering companies (SEC), including procedures, interactions, and workflows [11]; recommendations for computer programs and communication networks; and other variables necessary for success.

This paper is structured on the basis of a robust bibliographic review of scientific journals in the area, together with studies of expert recommendations that define the problems of the structural design phase and the potential of the BIM methodology. This methodology is structured on the basis of six sections: company analysis, reformulation of the BIM objective in the company, requirements for the adoption of BIM, determination of the "implementation gap," strategies and planning for implementation, and finally, the assessment and monitoring.

2. Literature Review

Current procedures in structural engineering companies are dynamic and iterative. The analysis and design of structure is based on trial and error processes, until the convergence of structural models and defines and designs the various elements that make it up [12]. This process is also constantly fed by changes coming from the senior structural engineer and/or the architect, generating recurrent revisions of the design that must be studied again. In addition, the interactions between the various professionals in this phase are high but poorly systematized and not optimized, establishing artisan communication channels, which causes lack of information and disconnection [1]. These situations entail a series of interaction problems, both within the company and with external professionals, which translate into productivity losses, in addition to the fact that they have not incorporated collaborative work methodologies to optimize their processes [2].

Building information modeling (BIM) is a collaborative work methodology that seeks to connect people, processes, and digital models in building and infrastructure projects, thereby allowing fluidity in the transfer of information and communication [1]. Thus, with a digital graphic representation of the physical characteristics and functionality of the project, it is sought to manage the phases of design, construction, and administration throughout the life-cycle, considering relevant the information associated with the graphic representation, which allows its work and use for various functions [13].

The need for BIM in the early stages of the project is very relevant [14]. The MacLeamy time-effort distribution curve in Figure 1 shows how capacity to influence costs and changes of a project is greater at the design stage and decreases significantly as the project enters the operation phase (curve 1). At the same time, the cost of making changes is very low during the design phase and quite high in the operation phase. Curve 3 shows traditional design behavior, while curve 4 shows how performance shifts to the left when using BIM technologies, allowing for greater ability to make changes at lower costs [15]. It should be noted that displacement of the curve necessarily involves interactions between all phases of the project; this is where BIM and nD modeling have great potential for industry integration [16].

Specifically, BIM has been demonstrated to facilitate communication and information transmission between professionals from different disciplines during the structural design process, allowing greater accessibility and constant updating of information, even in real time [17]. BIM enhances knowledge sharing management, reducing the time and cost of solving problems related to constructability and projects coordination [18]. In addition, it allows architects and structural engineers (bidirectional flow) to visualize modifications and conflicts and assists immediate decision making, significantly reducing rework and optimizing project times and costs [8]. Also, by detecting errors in advance and automating variables that were traditionally used in "manual" processes, BIM also enhances automation of detail engineering and documentation processes, reducing work times and increasing project quality [19, 20]. The possibility of integrating structural and nonstructural elements into the model controls performance of the whole. Once structural analysis has been carried out and member sections have been verified, BIM allows SEC to monitor how structural behavior affects nonstructural elements and/or other components of the project (considerations that would otherwise be too complex without the use of this type of tool). Thus reductions in costs for repairs when the structure is used differently, or when affected by adverse natural effects (earthquakes, hurricanes, among others) [7].

The correct exchange, quality information extraction and storage, are relevant to the success of BIM. There, the importance of universal archives, such as IFC format, is relevant to the achievement of these objectives [21].

In spite of the above lack of agreement, there are methodologies or guidelines for BIM implementation, mainly from developed countries such as the United States, Holland, and the United Kingdom, among others. These lists of recommendations for BIM are structured around project development [22], the roles included, and the tasks, objectives, and responsibilities of each of the participants in the process [23]. However, the steps for implementing BIM in companies remain to be defined: plans, training, studies, progressive changes, etc.

It is important to clarify that BIM implementation does not modify design criteria or standards, but rather restructures the way professionals and processes develop and interact with each other. Thus, each team member becomes aware of the importance and objectives of the process, has

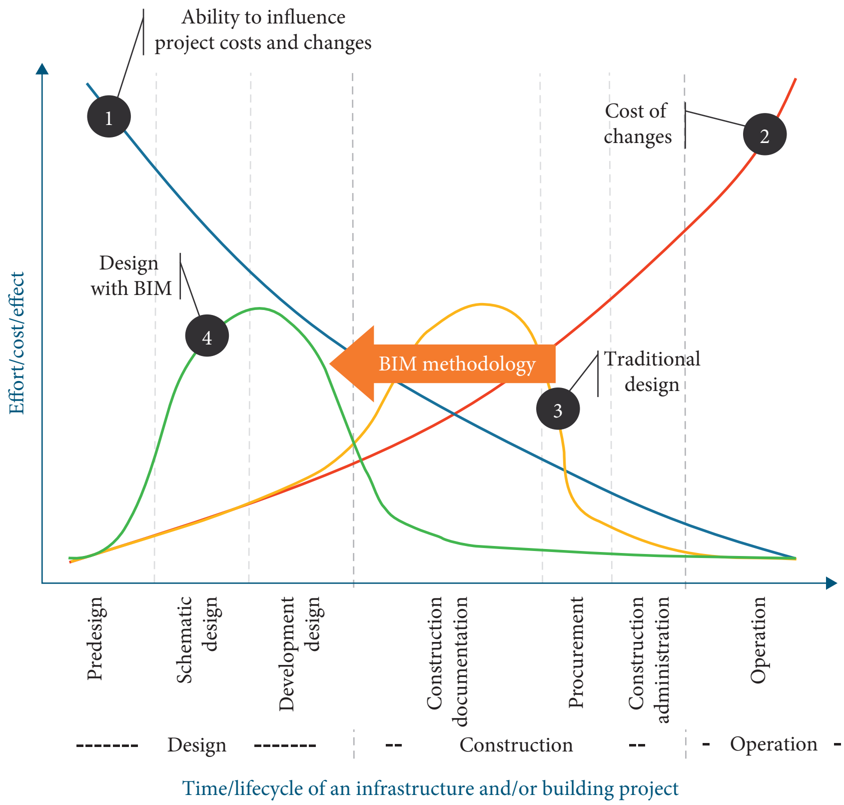


Figure 1: MacLeamy time-effort distribution curves in construction [15].

well-defined roles and responsibilities, and acquires knowledge of the requirements for skills, competencies, processes, and interactions needed for project success. Furthermore, the implementation plan serves as a guide for new professionals to join the task at hand and is a reference for future evaluations of success in the company [10].

3. Methodology for BIM Implementation in SECs

The BIM implementation methodology for structural engineering companies (SEC) has different stages, as shown in Figure 2. The methodology maintains implementing manual principles from leading authors, methodological recommendations, templates, and guides of the "BIM Handbook" and the "Project Execution Planning guide" [23, 24] while expanding and adapting the same for SEC. It is mainly characterized by clear and flexible processes for company requirements, objective evaluations of resources and processes, real implementation requirements identified, and maximally optimized costs.

The requirements for an implementation methodology necessarily include recognizing the objectives, expectations, and approaches that a given company wishes to achieve when incorporating BIM methodology; identifying roles, teams, and functional structures; planning gradual scales and speeds of implementation and training; and identifying the alignment of management and staff, along with a detailed program of action, according to experiences reflected in various research documents [25–27]. In addition to the above recommendations, the model in the present paper has additional components to generate a more complete and flexible implementation methodology, summarized in six major sections: company analysis; reformulation of the BIM objective in the company; requirements for the adoption of BIM; determination of the "implementation gap"; strategies and planning for implementation; and finally, assessment and monitoring.

Below, each section of the methodology as shown in Figure 2 is detailed.

3.1. Business Analysis and Diagnosis. In order to refocus company activities using BIM methodology, it is necessary to understand how the organization works, what resources it possesses, and its expectations and projections for the future. In this way, the implementation will be aligned with the objectives, vision, and mission of the company, will take advantage of available resources, and will generate the most suitable plan. From the very first contact with the company, management staff must be instructed on BIM in order to bring them closer to the methodology and show them its potential. Afterwards, in order to carry out a complete study of company operations and characterize its needs, all the necessary information points below are to be developed.

3.1.1. General Information. General, information on the organization is to be collected, which is useful for identification of the company and future management. The

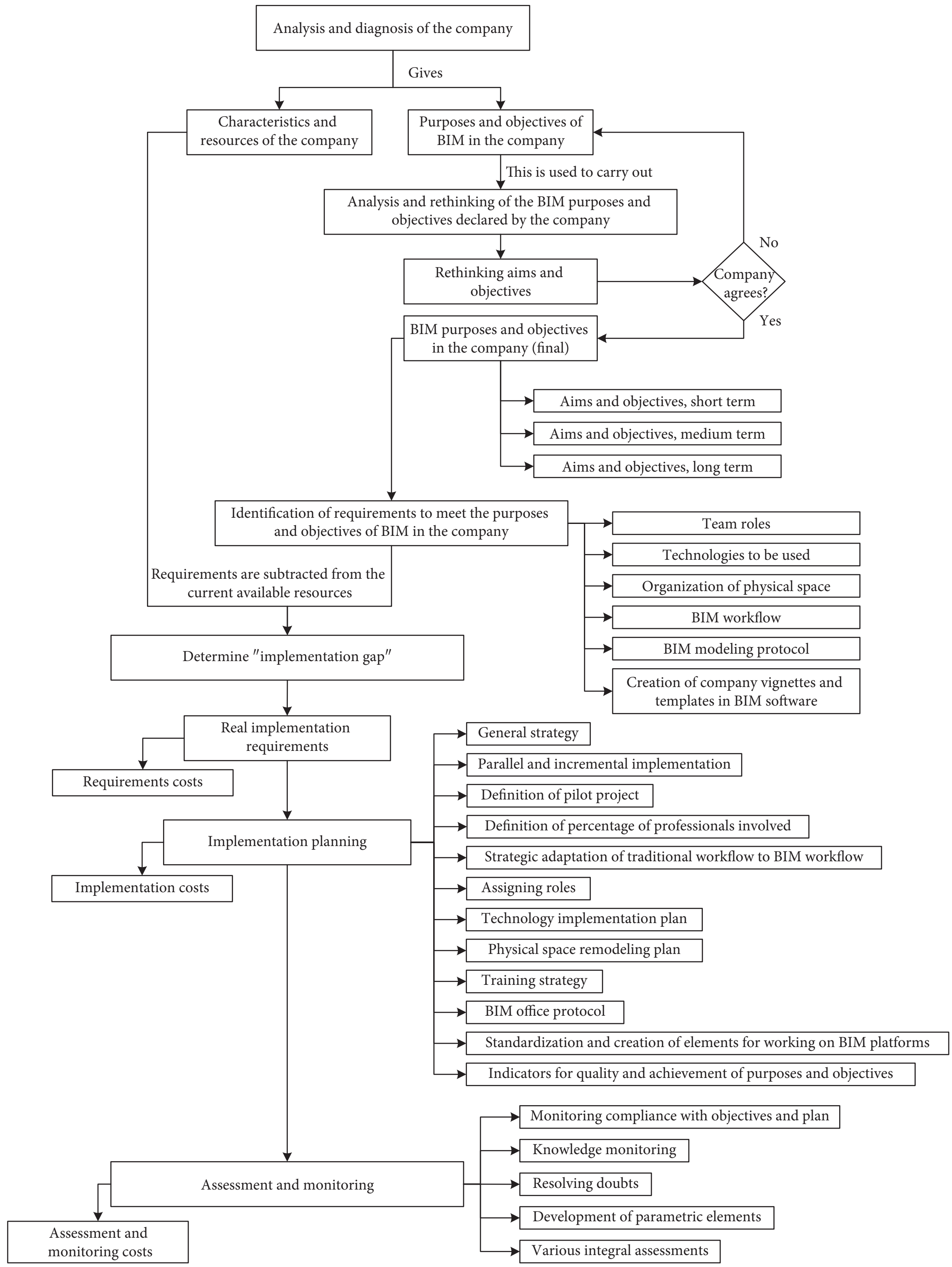


Figure 2: Methodological model for BIM implementation in structural engineering companies (SEC).

following is requested: name of the company, address, contact, professional contact, organizational chart, number and type of professionals, working hours, and timetables available for training sessions.

3.1.2. Focus and Expectations of the Company. The implementation plan should be aligned with company vision, mission, and the objectives it seeks to achieve through BIM implementation. Thus, three perceptions should be defined:

(1) vision of the organization; (2) target market and projects developed; and (3) purpose of BIM implementation.

Identifying the vision and mission of the company implies understanding its own definitions of how it was conceived, how it has acted, and how it projects itself towards the future. Respondents should be ready to answer how BIM will help meet these institutional objectives.

The organization should be explicit about their target market and the size, type, and approximate duration of the project it is developing in order to timely inform requirements and provisions for respective contractors in alignment with BIM deliverables.

The organization must also state the objectives for which it wishes to adopt BIM. These may include lower costs, improved project quality, reduced time, participation in new markets, and/or regulatory requirements, among others. The organization delivers these objectives expressed in expectations of concrete goals (tasks and dates).

3.1.3. Evaluation of Available Resources. Available resources are evaluated through three categories: (1) human resources; (2) technological resources; and (3) physical space and office furnishings. For each of these, it is necessary to know investment, renovation, and/or plans for expansion in order to identify previously assigned resources and align some implementation costs.

The human resources available are evaluated to obtain information regarding capabilities and competencies, with technical and personal skills such as: technical competencies (TC), personal and collaborative work skills (PCWS), mentality and willingness to change (MWC), and alignment with the vision and development of the company (AVDC). In order to obtain high levels of veracity during consultations, self-assigned scores from each professional (Pp) should be weighted against the evaluation of their direct supervisor (Ps), at the discretion of the evaluator. Table 1 shows the skills and abilities that should be consulted with company employees. Items should be added or removed for specific computer programs, depending on the context of the company. The list shown, while not exhaustive, includes the most frequently found programs in offices surveyed.

Table 1: Items for measuring human resources.

Item		Competencies
TC	1	Mastery SAP2000
	2	Mastery ETABS
	3	Mastery of SAFE
	4	Mastery AutoCAD 2D
	5	Mastery of AutoCAD 3D
	6	Advanced mastery EXCEL
	7	Mastery of the programming program (MatLab, other)
	8	Mastery structural robot
	9	Mastery of advance steel
	10	Mastery advance concrete
	11	Mastery of tekla structures
	12	Master and other structure programs (please specify)
	13	Mastery revit architecture
	14	Mastery revit structure
	15	Mastery revit MEP
	16	Mastery archicad
	17	Mastery of navisworks
	18	Mastery of "working in the cloud" (please specify)
	19	Mastery of other BIM programs (please specify)
	20	Mastery standards of structural design
	21	Mastery of plan detailing standards
	22	Mastery of BIM methodology
PCWS	23	Leadership
	24	Collaborative work
	25	Management control skills
	26	Problem solving skills
	27	Creativity
	28	Conflict management
	29	Ability to persuade
	30	Communication skills
	31	Negotiation skills
	32	Sense of discipline
MWC	33	Quality orientation
	34	Self-study capability
	35	Flexibility to change
	36	Readiness for training and new studies
AVDC	37	Organizational sensitivity
	38	Alignment with company vision
	39	Alignment with the company's mission
	40	Commitment to the company

Inventory of the company's technological resources should include hardware and software; all software or virtual tools and/or platforms used should be accounted for. Thus, at least 3 broad categories of these media items are available: equipment (brand, model, processor, video card, RAM, hard disk, and video adapter); software and/or virtual platforms (name, developer, local provider, type and cost of licenses, description of use); and local and/or "cloud" servers (brand, model, capacity, and description of the network).

BIM implementation requires fluid interaction among project team members, and it is essential that the physical workspace within the company allows for this type of interaction [24, 25]. This is why the organization must submit its plans for the existing physical facilities, detailing locations of facilities, networks, furnishings, and people in order to understand staff interaction conflicts within the office and to propose restructurings adapted to the current scenario during BIM implementation.

3.1.4. Analysis of Current Deliverables. The company should report current deliverables. The need to know the characteristics of organizational deliverables lies in the fact that the product achieved through BIM implementation must align with current indicators.

Any deliverable an organization currently has should be included in a document called the "Traditional Design and Drafting Practices Manual," which details development of the plans made under traditional work methodology and standardizes work done within the SEC. The aim is for the organization to clarify three characteristics: (1) minimum regulatory framework required; (2) standards set by the SEC above regulatory requirements; and (3) established checkpoints for verifying information at all levels of project development to prevent the spread of errors and to seek timely correction. Many companies already have this document for office criteria, so its identification should not be complex.

3.1.5. Evaluation of Current Processes. Evaluation of current processes (and components thereof) within the organization is developed along three lines: current workflow and processes; programs used in each activity; and current problems. Workflow and processes within the organization are to be identified for all types of resources and deliverables. In general, companies in the field do not formally define processes; however, professionals usually do have a clear definition. The evaluator then translates the declared processes into a workflow template. For each of the activities declared within the workflow, any programs used to develop or support work should be indicated. This helps to identify current problems in the organization. To this end, Muñoz [2] published a nonexhaustive set of 25 common problems that occur in structural engineering offices, which are reproduced in Table 2.

Table 2: Typical problems in structural engineering companies (SEC) [2].

Interaction	No.	Problems in SEC
I-E	1	Various returns of the projects to architecture
	2	Delay in return of plans from architecture, protested by the SEC
	3	No notification or specification of changes in plans from architecture
	4	Inefficient communication channels with architecture
	5	Few direct coordination meetings with architecture
	6	Lack of initial coordination (defining channels, means for working, and feedback) in early architecture-engineering interactions
	7	Differences in modeling criteria between architecture and SEC
	8	Delays in deliveries due to questioning of calculations based on differences in design criteria between project review offices
	9	Projects returned to the SEC due to doubts/errors identified during the construction phase
	10	Postdelivery changes to total costs of bulk work (reduced costs)
1-E/I-I	11	Loss of information from central source (architect, client) when passing across the desks of senior engineers, coordinators, up to the executing project engineer
	12	There is no logbook/record of project modifications
	13	Presence of downtime in projects
I-I	14	The exchange of information between the engineer-designing draftsman is "manual" (handwritten plans, verbal indications, etc.)
	15	Large number of reworks by the designing draftsman due to recurring changes
	16	Errors in final structural plans
	17	Excessive work for designing draftsmen because of large amount of detail in the projects
	18	Redrawing of architectural plans to structural plans
	19	Changes in analysis models (partial or global) due to project modifications
	20	Identification of errors and/or omissions in near-completed projects
	21	Low internal control of ongoing activities and projects
	22	Decreased efficiency due to multiple jobs performed in parallel by one professional
	23	Excessive rework by the project engineer
	24	Large number of spreadsheets (excel, etc.) that make the design process slow and cumbersome
	25	Many projects with similar deadlines as all clients want their projects to be completed quickly (everyone needs theirs "yesterday")

3.2. Analysis and Rethinking of the Purpose and Objectives of BIM as Stated by the Company. The statement of objectives that the organization seeks to achieve by incorporating BIM in some cases may come from partial or misconceived knowledge of, rather than the full potential embodied in, BIM. In view of this, once company objectives have been defined and placed within the framework of its characteristics (size, resources, etc.), the objectives to be achieved through BIM must be reconsidered in order to optimize resource use for investments, or to place concrete goals on the expectations raised. The fulfillment of objectives should also be distributed throughout the short, medium, and long terms.

3.3. Requirements for the Adoption of the BIM. The implementation plan identifies all the requirements necessary for an SEC to work with BIM by considering the important contributions from current organization attributes and resources.

3.3.1. Team Roles. Since the implementation plan in this paper focuses on SEC, it is necessary to adapt traditional generic BIM roles to the development of structural design and calculation under BIM methodology [28–30]. The construction of BIM roles for the work team expands and adapts the four roles and 15 competencies from the BIM role matrices as proposed by both the Dutch BIR [31] and Chilean BIM Plan [25], given that they propose in a simple and complete way the generic roles that must be assumed in the BIM methodology. In addition, the BIM approach of the United Kingdom [E] has been studied, pioneers in BIM worldwide, considering the articulation of tasks and roles that they include, focused on aspects of training and skills that must be assumed. It is important to note that BIM roles assign responsibilities and functions to different members of the work team; they are not necessarily related to specialties or positions, and moreover, they can be developed by more than one person or allow one person to exercise more than one role. Table 3 shows the five roles the current SEC BIM plan considers: BIM coordinator, BIM modeler, BIM reviewer, BIM project engineer, and BIM leader. In addition, the skills and abilities of the roles detailed by the Chilean BIM Plan and the Dutch BIR have been adapted to numerical parameters in order to quantitatively establish requirements for the different attributes and capabilities for professionals assuming a specific BIM role. Table 4 shows

Table 3: Characteristics of BIM roles.

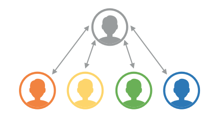
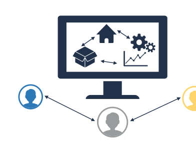
Role	Main characteristics	Model
BIM leader	Responsible for commanding BIM implementation in the organization, defining protocols, and guiding the BIM execution plan (BEP). Must have extensive knowledge of BIM methodology.	
BIM reviewer	Responsible for verifying that the modeling is correct, based on technical and normative aspects and according to organizational protocols.	
BIM coordinator	Articulator of the BIM process in the organization, responsible for model validation and coordination. Serves as a point of contact among different modelers and specialties—must comply with the BEP and be fully aware of BIM standards, mandates, and regulations.	
BIM modeler	In charge of developing BIM models, including 3D visualizations and information associated with the elements. Must have a broad mastery of the related computational tools and a broad knowledge of the discipline modeled.	
BIM project engineer	Professional who performs modeling, analysis, and structural design, but who has acquired skills to partially or totally develop such work under BIM methodology and computational platforms.	

Table 4: Competencies and capacities a professional must have to assume a certain BIM roles.

No.	Skills	BIM leader	BIM reviewer	BIM coordinator	BIM modeler	BIM project engineer
1	Leadership	5	2	3	1	3
2	Training	4	4	4	4	4
3	Collaborative work	5	4	5	3	4
4	Management control	5	3	3	1	3
5	Problem analysis	5	3	5	2	5
6	Creativity	5	3	4	3	4
7	Organizational sensitivity	5	2	3	2	3
8	Vision	5	3	3	3	3
9	Conflict management	5	3	4	1	2
10	Persuasion	5	3	4	1	1
11	Negotiation skills	5	2	3	1	2
12	Communication skills	5	3	4	1	3
13	Quality orientation	5	5	5	5	5
14	Sense of discipline	5	4	4	4	4
15	Constant self-learning	4	4	4	5	4
16	Flexibility to change	4	3	4	4	3
17	Industry needs and challenges	5	1	1	1	2
18	BIM methodology	5	3	3	3	3
19	BIM implementation strategy	5	2	2	2	2
20	BIM execution plan (BEP)	5	2	2	2	2
21	BIM standards and norms	5	4	4	4	4
22	Structural design and calculation	2	1	1	1	5
23	Use of structural calculation program	2	1	1	1	5
24	Using the BIM structural calculation program	2	1	1	1	5
25	Use of BIM modeling software	2	5	5	5	5
26	Use of BIM coordination program	2	5	5	3	2
27	Use of BIM communication platform	5	4	5	4	5

this quantitative measure of skills on a scale of 1 to 5, where 1 represents a low competency level required and 5 high.

3.3.2. Technologies to Be Used. Software interoperability chosen for working in BIM environments is important to the success of the workflow proposed by BIM methodology. While industry foundation classes (IFC) look to be a universal language to connect many software programs in BIM environments, the technology is not yet fully resolved; the only 100% effective way to correctly connect models from different platforms is currently through the use of native programs, i.e., from the same provider or with partner providers. In addition, in view of the variety of options offered by the market, it is necessary to choose the specific tool that best solves objectives sought, weighed in favor of its scale of use and interoperability.

Each BIM professional will have different uses for each computer program [32], and thus differing levels of mastery to successfully perform tasks (though further training is not to be disregarded) within the framework of company-defined objectives. By accounting for these variables, it is possible to optimize and plan training resources.

BIM software requires greater computing power. The recommendations given in Table 5 correspond to specifications provided through consensus among program brands and expert user opinions [33, 34]. Required hardware capabilities are closely related to the size of the projects to be modeled; thus, these are specified to reduce equipment costs that, in the short or medium term, would not be used to maximum potential. Five evaluation categories are defined: operating system, processor, hard disk, RAM, and video card. Table 5 shows general hardware requirements and provides recommendations according to project size. "Type I" projects are considered to be single-family houses and small residential buildings; "Type II" projects are considered to be medium-sized and large residential buildings, and medium-sized office buildings and complex works (e.g., medium-sized clinics); and "Type III" projects are considered to be large skyscrapers and complex works (e.g., large hospitals, airports, etc.).

Since the core of BIM is the connection of processes, files, models, and professionals, a network (server) is required to connect all office team member computers. For example, working under the "Windows Server" platform (Microsoft) has several security advantages and cloud storage capabilities. In addition, visualization and coordination of models must be possible from any physical location. To this end, the use of cloud computing environments, such as A360, BIMsight Key, or Solibri Model Viewer, among others, is recommended to allow interconnected work on the Internet with the rest of those involved in a project. In the future, when there is a project with a large amount of data, computer supports will be necessary to manage it. Optimizing the Big Data of the projects will be relevant for its management [35, 36].

3.3.3. Organization of Physical Spaces. The distribution of physical spaces directly affects how professionals develop their activities, even more so within a collaborative environment such as BIM. To achieve greater and better interactions, it is necessary to remodel the workspaces within the company. Field observations were made to 10 structural engineering companies in Chile, noting that in all of them, the engineers were separated from the modelers. In addition, the professionals declare that there are communication problems between engineers and modelers, mainly because of how the jobs are distributed, having to move from place to consult the projects. Based on field observations made in various companies in the area, a physical arrangement called "3 pairs" is proposed (Figure 3). This arrangement has professionals together at the same time in 3 types of pairings: engineer-modeler (blue-yellow interaction); modeler-modeler (blue interaction); and engineer-engineer (yellow interaction). Thus, engineers are able to communicate directly with modelers, and engineers as modelers (designer draftsmen) are able to provide feedback to each other, etc.; in short, each may directly consult technical and theoretical doubts of their profession with the colleague next to them. It is recommended that there should be more experienced professionals at the ends of the "chains," where there is only one professional left without a paired colleague, since they will make fewer consultations with their colleagues, spending less time overall.

At the same time, the professional BIM modelers and coordinators must be in an integrated collaborative workspace linked to the integration of other specialties (besides the engineering-designer calculation work) in what has been termed the "extreme collaboration environment" [37]. Figure 4 shows how this room should be organized. The use of a big room is useful, to bring together the owner and the other disciplines, achieving an integrated collaborative process [39].

Here, professionals can work from their personal computers and view a central model on screen. In addition, the extreme collaboration environment serves as a meeting and decision-making room for all project members (including architects and builders) to identify errors or ways to construct the models. In this room, real physical collaboration is achieved among the different professionals involved in the project, with real-time visualizations of how decisions are materialized (in 3D).

3.3.4. BIM Workflow. Figure 5 shows the ideal SEC BIM methodology workflow diagram. The proposed BIM methodology workflow provides fluid communication and document generation processes and facilitates model revision, reducing time spent overall. This workflow is an adaptation of generic BIM flows proposed in the project execution planning guide [22] and is based on professional interactions in a central model: the BIM platform for a given SEC (Revit, for example) will contain volumetric models, reinforcement steel or other structures, as appropriate, and detailed designs and drawings [40]. Thus, all the models may be "superimposed" in order to visualize conflicts and optimize interaction. The workflow also proposes coordination meetings among all the professionals to advance criteria and/or agree on changes.

Table 5: Hardware recommendations for use of BIM software as of 2018.

No.	Item	General characteristics		Recommendation, by type of project
1	Operating system	The use of Microsoft® Windows® (not Linux or Apple), higher than 7, 64-bit version, is recommended.	I II III	Microsoft® Windows® 10, 64 bits Microsoft® Windows® 10, 64 bits Microsoft® Windows® 10, 64 bits
2	Processor	Single or multicore Intel® Pentium®, Xeon®, or i-series processor or equivalent AMD processor (with SSE2). Select version with the highest possible speed.	I II III	Intel® core I5 Intel® core I7 Intel® core Xeon
3	Hard disk	Preferably solid state disks (SSD) or traditional HDD disks of 750 GB or higher. 5 GB of free disk space is required.	I II III	Traditional 1 TB HDD disk 128 GB SSD + traditional 1 TB HDD disk 500 GB solid state disk SDD
4	Ram	RAM of 8 GB or more.	I II III	8 GB RAM 16 GB RAM 32 GB RAM
5	Video (or graphics) card	NVIDIA Quadro cards: 2000 (1024 MB), 4000 (2048 MB), 5000 (2560 MB), 6000 (6144 MB), k-series and above, or similar to the above. The video (or graphics) card must be dedicated, not integrated. AMD counterparts (less recommended) may be used.	I II III	Dedicated NVIDIA graphics card Dedicated NVIDIA graphics card Dedicated NVIDIA graphics card

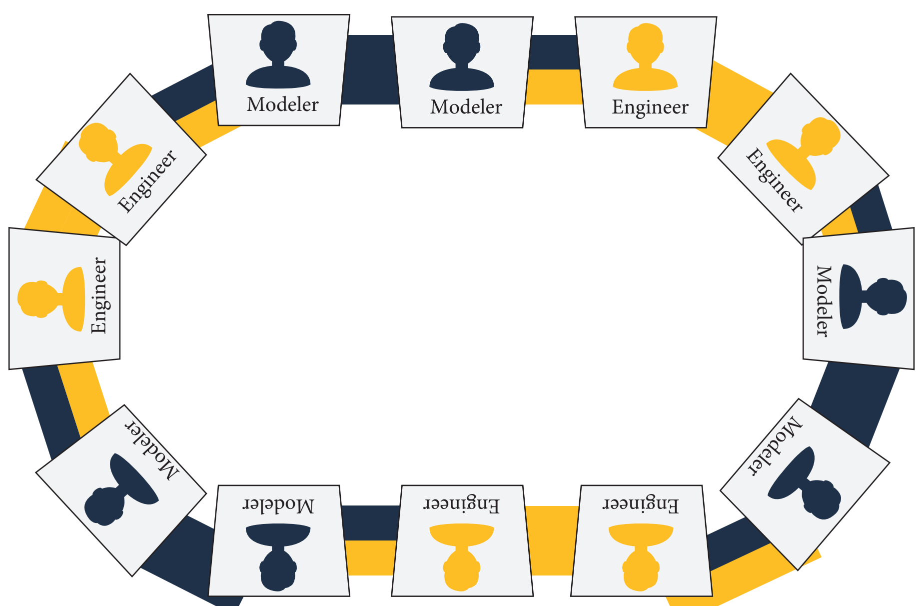


Figure 3: Organization plan for the ideal BIM physical space, "3 pairs".

3.3.5. BIM Protocol. The structural design companies have their own manuals of procedures and standards that define the work they do, which are based on the standards and national design codes. Currently, based on the documented CAD-2D drawings (complemented by three-dimensional analysis models), companies are guided by 2D design manuals and drawing practice manuals to standardize their design and detail outputs. Now, to work in BIM, counterpart document should be generated for documentation under the BIM methodology, to be called the "BIM Protocol." This will contain the minimum regulatory framework required, standards established by the SEC (over and above the regulatory requirements for modeling, according to the objectives defined with BIM), and the control points for verifying information at all levels of project development in order to prevent the spread of errors and seek their timely correction. This should be aligned with the BIM execution plan (BEP) and look to standardize model generation on BIM platforms, establish work platforms, define channels, and connect models and professionals. It will be a dynamic document, adaptable to regulatory requirements and technological changes. Table 6 shows recommendations for BIM Protocol content.

All information from the BIM Protocol that reiterates that of the Traditional Design and Drafting Practices Manual should be explicitly incorporated in this protocol (ideally referencing the traditional standard as a user guide).

In addition, office project plans should explicitly indicate any particular characteristics of the deliverables generated, so as to check that the work is being properly standardized,

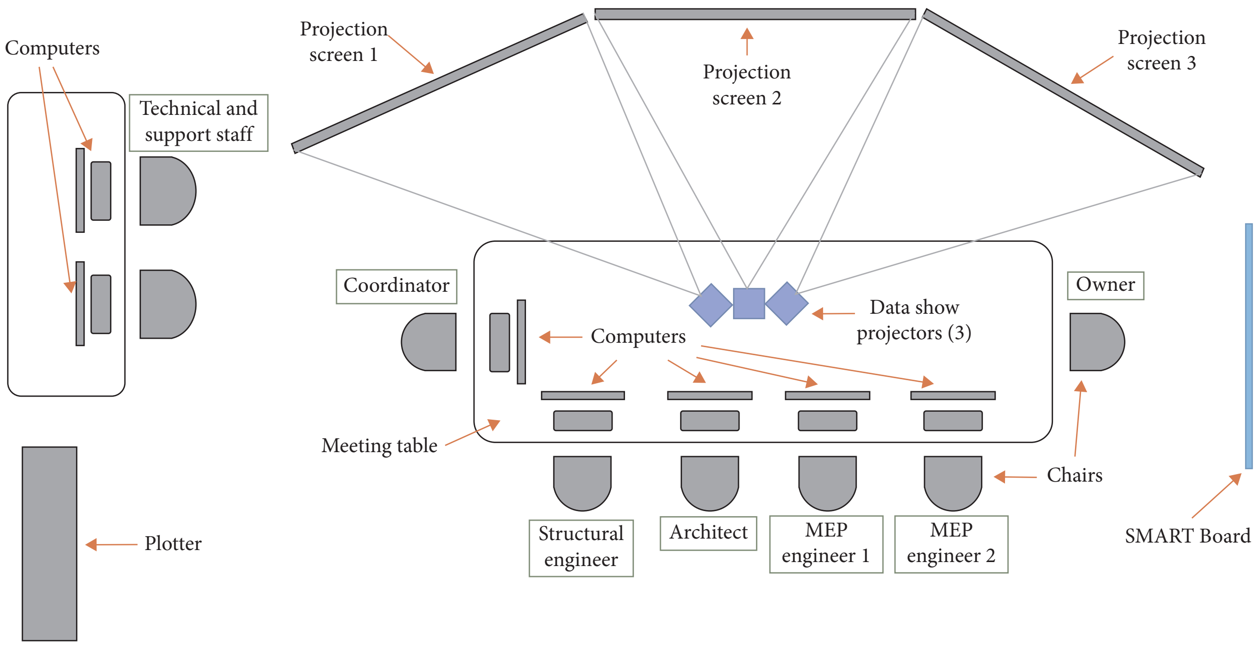


Figure 4: Extreme collaboration environment [38].

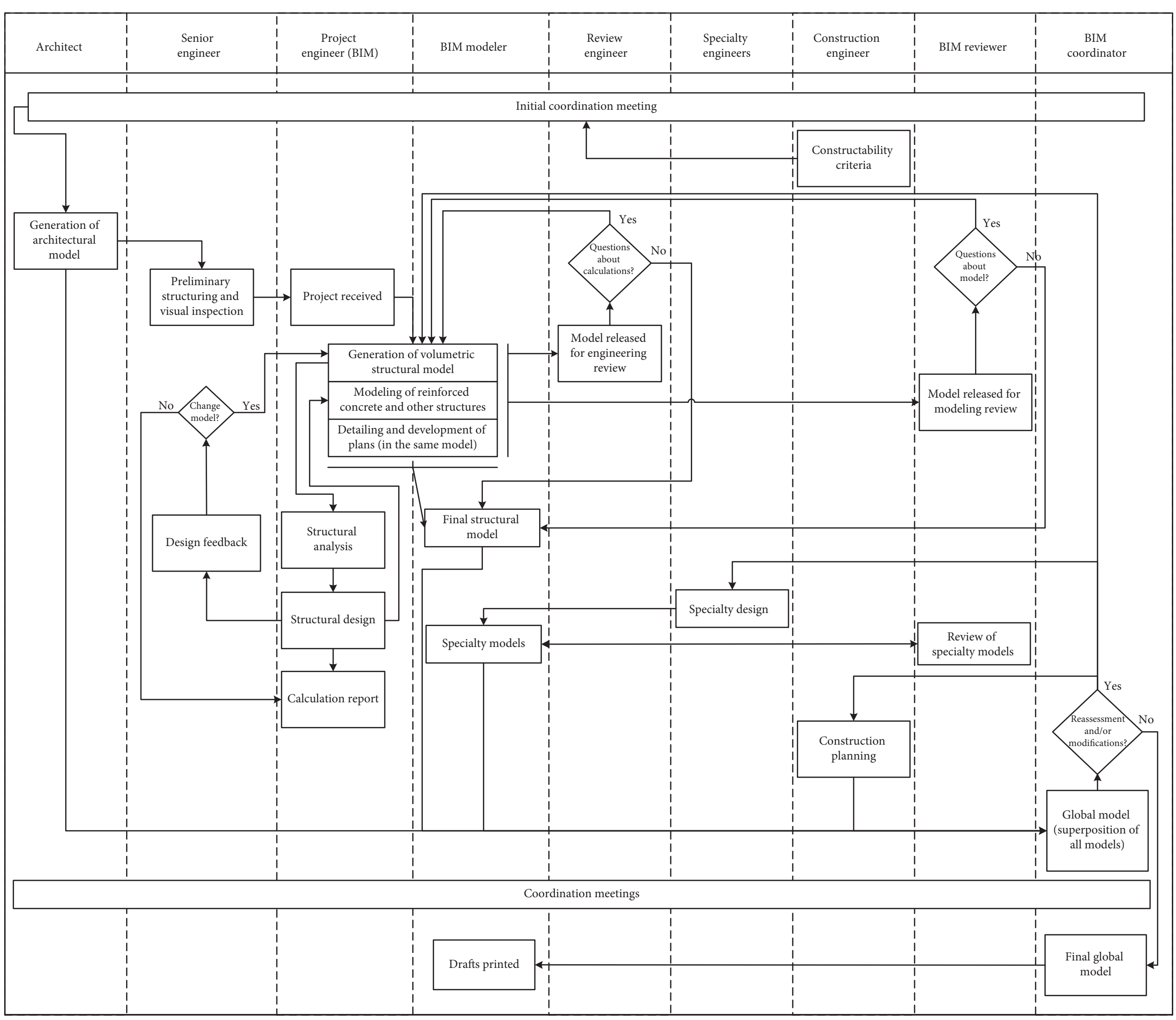


Figure 5: Workflow under the BIM methodology.

Table 6: Recommendations for BIM Protocol.

Item	Description
Responsibilities	Commitments, staff in charge, implementation, supervision, and compliance responsibilities are identified, established, and assigned.
Project development and workflow	All the phases of a project, input documents, and the deliverables of each (background, calculation report, models, documented) must be indicated. Workflows between internal and external professionals are detailed.
General terms, definitions, and characteristics	General aspects of the deliverables must be made explicit according to the criteria of the company in particular. Define: formats, bullets, updates and revisions, scales and work units, dimensions and sizing, among other characteristics.
Basic modeling elements	Basic aspects of modeling should be pointed out regarding how certain actions should be developed in these BIM platforms. Detailed design references, program commands used, characteristics of parametric elements, types of annotation, among others, are indicated.
Contents of plans	The final plans, which will be produced in coordination with the BIM model, must comply with the traditional specifications of the SEC, so their content and characteristics do not vary from those specified in the company's Traditional Design and Drafting Practices Manual.
Definitions and considerations for BIM	The team must be contextualized in the new work methodology, according to the following aspects: single work model (a cloud-based file in which several elements are simultaneously combined), model transcendence (where any modeling must be useful "upstream" during later stages), LOD and LOI (levels of detail and information in the models), IFC and interoperability, importance of fluid communication, BIM computational tools, interconnected work "in the cloud," among others.
BIM modeling strategies and recommendations	Clarify recommendations such as: general structuring of the modeling (partitioning the model into levels and specialties, in order to improve workability), generation of phases (organizing different temporal states of the project, e.g., demolition, construction), construction considerations (replicating the modeling as it is built in reality), considerations for material take off, model coordination, order in the project environment, subdivision by system colors, among others.

especially in the initial stages of the project. Once the first models have been generated, examples of these should be attached to serve as a guide for future professionals and/or for queries regarding how particular complex situations were modeled.

This protocol is meant to be flexible and may be modified in the future provided that there is progress in BIM objectives. For example, this protocol may incorporate new planning or construction tactics (when a construction model is generated, for example).

3.3.6. Business Requirements for BIM Software. It is assumed that the company will currently have a "design" of how it structures and delivers its products (drawings), as detailed in its "Traditional Design and Drafting Practices Manual." In view of this, it is necessary to generate all the templates used in BIM program documentation, in such a way that the office professionals only use models from previously created templates. These resources should be made available in the initial phase of implementation and handed over to the office for free use.

3.4. Determining the Implementation Gap. BIM implementation undoubtedly represents an important cost for the company, which is why it is necessary to optimize the use of current resources, i.e., to refocus and adapt them to the work under the BIM methodology. After identifying objectives and establishing the tools to be used, BIM methodology proposes that current resources should not be ignored; on the contrary, they should be considered as the starting point for implementation. From there, the resources missing to reach the total requirements should be established. This establishes the concept of the implementation gap, as shown in Figure 6.

Thus, BIM requirements (in terms of job roles, technologies, physical space, BIM workflow, modeling protocols, and templates) must be subtracted from currently available company characteristics and resources in order to implement only those missing requirements. In other words, technological implementation does not start from zero; the company will already have equipment that can be totally or partially reused, from which it is sufficient to acquire parts or improve systems to meet the requirements of BIM.

By determining the implementation gap, it will be possible to identify the costs of the actual implementation requirements. The economic cost of the latter will be lower than would be requirements that do not consider the current resources of the company and thus would be less impressive for company managers looking to program future investment.

3.5. Implementation Planning. Implementation planning should clarify, specify, and contain details of the actions that

Figure 6: Determining the “implementation gap”.

will be carried out. The general guidelines provided must be adapted to the particularities of the company. The points discussed in this section should be contained in the BIM execution plan (BEP), which guides the successful development of BIM projects. Essential planning points are discussed below, and details of the objectives and contents that each section seeks are given.

The recommendations outlined below have been based mainly on the methodological recommendations of the “BIM Handbook” [24] and the templates and guides of the “Project Execution Planning Guide” [23], together with recommendations for implementation experiences declared in the literature [25–27]. All of them declare themselves considering the specific processes that are developed in the structural engineering companies, focused on the work, professionals, and dynamics of structural engineering companies.

3.5.1. General Strategy. The general strategy should be the initial motivating impulse for the entire work team, with the company’s vision and mission strongly present. It should indicate the objectives of the BIM (previously defined with the company), the scope of the implementation plan, and a general timeline indicating the actions required to achieve the goals.

3.5.2. Parallel and Incremental Implementation. A parallel and incremental implementation is to be developed in the company. On one hand, the implementation will be incremental; that is, there will be training and stages for implementation (or uses) that, once successfully completed, will allow for the company to proceed implementing the next. In this way, quality will be assured in the fulfillment of small objectives, avoiding dragging errors downstream. On the other hand, the implementation is to be carried out in parallel with traditional techniques (so as not to jeopardize the current project). Parallel work can become part of the real chain once mastery of that phase or objective has been successfully achieved; that is, in subsequent projects, work previously done in parallel (but now validated) can be incorporated into real process lines. Thus processes dominated by professionals are continuously incorporated.

3.5.3. Definition of a Pilot Project. The implementation process is to be carried out with a pilot project, which may be a current company project or one already completed. If a current project is used, its implementation on BIM platforms should be carried out in parallel with the work carried out under the traditional methodology; in this way, the changes in work methodology and the ease of use provided by the BIM platforms can be demonstrated with evidence. On the other hand, when working with a previously completed project, there are benefits in contrasting implementations under BIM vs traditional methodology (e.g., how previous problems are now simplified with BIM), as well as comparisons of results once the pilot has finished (results from material take off for the previous project, for example).

3.5.4. Definition of Percentage of Professionals Involved. The professionals to be trained in BIM should be established. For small and even mid-sized companies, BIM training and implementation should be done by all professionals in the company. However, in medium-sized or large companies, a group of professionals should be assigned. In small companies, it is much easier to manage and instruct a small group of people (strengthened by the likely closeness and trust among the work team) and to take their different professional roles into consideration. This is especially true given that there are not a sufficient number of professionals to assign specific tasks to each. On the other hand, large companies generally establish working groups and areas of expansion, and it would be unmanageable to work with all professionals in the first instance.

Rather, the aim is to generate a “BIM nexus” within the organization, which will generally be in charge of future expansion of BIM knowledge in the rest of the organization and with any new professionals who can be strengthened by formal training.

3.5.5. Strategic Adaptation to BIM Workflow. The requirements of BIM propose an ideal workflow; however, initially, a gradual incorporation of BIM into the office should encourage compliance with this flow, from partially to wholly. In view of this, the adaptation of the workflow should start with what the company has declared, reformulated, and oriented towards partial, gradual replacements and, eventually, ideal BIM workflow. The speed of these changes will be in accordance with the traceability of objectives achieved.

3.5.6. Assigning Roles. The selection of professionals that best meet the profiles required of new BIM roles is possible by identifying current competencies found in the roles of the work team, and the characteristics of each of the professionals that the office currently has. This selection should first be made with reference to personal and collaborative work skills, followed by technical knowledge; it is easier to train technical skills than soft skills.

3.5.7. Technology Implementation Plan. To define the technological gap of a company to work in BIM, it must have the following information: current capabilities of technologies and technological characteristics. Here, it is also important to know the plan for the acquisition and renewal of equipment and licenses in order to take advantage of any already planned resources in purchasing platforms and equipment necessary for the operation of the BIM methodology. This procurement schedule should also be planned according to the traceability of defined objectives.

The implementing company should be responsible for installing licenses and configuring the organizational intranet network. In this way, it will be possible to offer the service of sale of licenses (through a strategic partner distributor of programs) or to leave the choice open to the organization. In addition, there must be a technical team to install the necessary equipment and networks.

3.5.8. Physical Space Remodeling Plan. A remodeling plan should be proposed regarding resources of the physical space required by the BIM workflow and the company's current physical state in order to adapt to the size of the office. A gradual plan for site changes and/or a change to another branch, as planned with the owners, should be proposed. Here, it is attractive to know the acquisition and expansion plan of the organization, in order to channel it with the required changes.

In sequential terms, it will be imperative to first reorganize the teams, as shown in Figure 4, and then (based on the gradual progress of implementation and available resources) incorporate the office layout shown in Figure 5 and/or generate the necessary physical changes.

3.5.9. Training Strategy. Training strategies are organized into three focuses: initial general dissemination of the plan, methodological training, and technological training.

Once the action plan for the office is defined, it will be relevant to inform all professionals about what will be developed. This "empowerment" and "conviction" should begin with senior company management to ensure firm commitment to the project. It is important to achieve these high levels of commitment with the work team as well, since they will have to make the greatest effort in terms of training and time dedication. Specifically, there should be explanatory sessions and consultations about the plan to give the entire team written support for the actions to be taken.

Training in BIM methodology should be a priority. The methodology, its scope, and general challenges should be taught theoretically. Afterwards, there should be specific explanations of how the company will adapt in functional and strategic terms, how roles will be assigned to each member, and what implications the process will have. Failure to correctly understand this will have a strong impact on the success of the implementation. Group training sessions are to be established, along with provision of background explanatory material.

Technological trainings should be oriented around BIM role requirements and selected technologies. Program trainings should consider previous professional knowledge in order to optimize curricula of employees. If professionals do not have an official certificate for the knowledge they declare (from e.g., professional internships or academic courses), evaluations to measure their content mastery are convenient: an instrument may be developed independently or jointly with a university to provide proof of academic certification for professionals. In turn, training should be conducted by level and based on implementation progress so as to distribute resources invested in training over time.

It is preferable that the company provides training service through its own resources, subcontractors, or agreements generated with universities or private institutes. Ideally, trainings are carried out at the office. Content delivery should be closely related to the practical work in the defined pilot project.

3.5.10. BIM Office Protocol. The BIM Protocol, and the extent to which it has been reformulated from the Traditional Design and Drafting Practices Manual, should have the same guidance and order as the latter in order to facilitate and accelerate understanding of new requirements, details, and necessary reconsiderations. The implementing company is to be in charge of generating the document, requesting all the required background information from the company, and providing examples and recommendations for its use. The different updates the protocol undergoes as it evolves in the use of BIM should be monitored.

The company will not be able to start its work in BIM if it does not have this document or if it has not been disseminated and socialized by all the members of the team.

3.5.11. Standardization and Creation of Elements for Working in BIM. Vignettes, templates, parametric elements (families, for example), information requirements sheets, and interference detection sheets, among others, must be created and/or adapted so that, at the beginning of the pilot project, the office has all the necessary elements available in BIM platforms for the successful development of the project. The objective is that deliverables are plotted and visualized in the BIM platform (Revit, for example) with same details and characteristics as in 2D CAD (referring to the final product in plans). The indications for this will be set out in the office BIM Protocol.

3.5.12. Indicators of Compliance and Quality. Compliance and quality indicators are related to the achievement of BIM objectives and purpose within the organization. In this sense, the evolution of the implementation will be measured with respect to its degree of capacity, understood as company aptitude in developing BIM features and services; and maturity, understood as the degree, depth, quality, and repetition of BIM features and services [41]. The above measurements provide generic indicators of BIM methodology progress (and implications) in global terms; that is to say, they serve to compare and classify the company within a certain range that, for example, is useful in identifying compliance with a maturity profile requested by a contractor (for e.g., bidding bases). That said, in order to measure progress and fulfillment of proposed objectives, the topics necessary for the fulfillment of each objective (theoretical and technological learning and/or acquisitions) should be identified and evaluated into three possible categories (1 = not achieved, 2 = somewhat achieved, and 3 = achieved). With this, efforts can be redirected to reinforcing unsuccessfully learned content or to reviewing moderately acquired content. Evaluations should be conducted on a topic-by-topic basis, so as not to leave knowledge or implementation gaps in the course of the process.

3.6. Assessment and Monitoring

3.6.1. Monitoring of Compliance with Objectives and Plan. The process must exhaustively document all company actions carried out and decisions taken within the platform that the implementing company deems appropriate. This record should note progress and compliance vis-à-vis indicators. This will allow for the generation of plans and actions to reformulate and restructure scheduled actions not yet completed.

3.6.2. Knowledge Monitoring. The knowledge acquired by professionals should be constantly monitored. To this end, knowledge tests are to be conducted on the use of programs and methodology as aligned with the progressive advancement of knowledge professionals acquire. Such evaluations generated by the implementing company and/or by university or technical entities (house certification programs) certify professionals and thus increase the competitiveness of the work team (with respect to personnel training in bidding, for example). The type of certification is subject to the resources available in the organization [42].

3.6.3. Resolving Doubts. Active communication channels are to be established between the organization and the implementing company in order to establish means, times, and dates of assessments regarding procedures and technical aspects of the use of programs. Professionals are encouraged to self-teach and learn collaboratively with team members in order to gradually allow the organization to be self-sufficient.

3.6.4. Development of Parametric Elements. To facilitate modeling on BIM platforms, a family building service is to be provided. This service allows the company to optimize modeling times and access requirements of the projects they carry out. The family building service is not considered part of the initial costs of implementation, but is rather intended to be a contribution in the course of the development of BIM in the office.

4. Conclusions

A methodology was developed for BIM implementation within structural engineering companies (SEC). This methodology clearly and objectively shows how to carry out implementation and includes processes for analysis and diagnosis, rethinking of objectives, identification of requirements, planning, and monitoring of the proposal.

The methodology made explicit the instruments to perform the in-depth company analyses and include steps for gathering information on current expectations, processes, and resources in order to clearly identify the potential of the company with a view to BIM restructuring.

The requirements for the adoption of BIM have been detailed and consider roles of the work team, technologies and space distribution, BIM-focused workflow, protocols, and other specific elements necessary for the success of the implementation. This allows companies to identify implementation gaps and, subsequently, real requirements for optimizing current resources.

Points which must be considered while planning a BIM implementation were raised in regards to general strategy, parallel and incremental forms of implementation, work with pilot projects, adaptations to BIM workflow, efficient assignment of roles, technological and physical remodeling plans, training strategies, standardization and creation of elements in BIM platforms, and the generation of a BIM Protocol for the company with follow-up and assessment actions.

The proposed methodology, although considers computational tools and technology that should be used, does not specify how they connect directly with each other and does not detail the technical aspects for it to work. It has been prioritized in this paper to show how BIM should be implemented in methodological terms, given that it is considered essential in the success of the incorporation of BIM. The technical will be relative to the computational tools used and will vary in each case.

In general, emphasis is placed on how to address each of these situations that should consider a structural engineering company, with a view to solving its productive inefficiencies, associated with collaborative work and interconnection, and clear actions were delivered that lead to a successful implementation.

Finally, the implementation of the described methodology should be carried out in pilot companies, for its practical validation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was developed in the Civil Engineering School of the Pontificia Universidad Católica de Valparaíso (Chile), with the regular investigations. R. F. Herrera acknowledges CONICYT, PCHA/National Doctorate/2018, 21180884, for funding the graduate research.

References

[1] J. Freire and L. F. Alarcón, "Achieving lean design process: improvement methodology," *Journal of Construction Engineering and Management*, vol. 128, no. 3, pp. 248–256, 2002.

[2] F. Muñoz, "Methodology for the implementation of BIM (building information modeling) in the development of structural projects," Thesis, Civil Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile, 2017.

[3] S. Azhar, "Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry," *Leadership and Management in Engineering*, vol. 11, no. 3, pp. 241–252, 2011.

[4] D. G. Lee, J.-Y. Park, and S.-H. Song, "BIM-based construction information management framework for site information management," *Advances in Civil Engineering*, vol. 2018, Article ID 5249548, 14 pages, 2018.

[5] Z.-Q. Liu, Y.-G. Li, and H.-Y. Zhang, "IFC-based integration tool for supporting information exchange from architectural model to structural model," *Journal of Central South University of Technology*, vol. 17, no. 6, pp. 1344–1350, 2010.

[6] A. Cohen and C. Snell, "Climate change and the bottom line: delivering sustainable buildings at market rate," *Architectural Design*, vol. 88, no. 1, pp. 110–115, 2018.

[7] D. Asprone, A. Salzano, E. Cosenza, and G. Manfredi, "Building information modeling: nuove frontiere per l'ingegneria strutturale," in *Proceedings of Italian Concrete Days Gionate AICAP 2016 Congresso CTE*, Rome, Italy, October 2016.

[8] Z. Liu, F. Zhang, and J. Zhang, "The building information modeling and its use for data transformation in the structural design stage," *Journal of Applied Science and Engineering*, vol. 19, no. 13, pp. 273–284, 2016.

[9] C. Robinson, "Structural BIM: discussion, case studies and latest developments," *Structural Design of Tall and Special Buildings*, vol. 16, no. 4, pp. 519–533, 2007.

[10] P. Smith, "BIM implementation—global strategies," *Procedia Engineering*, vol. 85, pp. 482–492, 2014.

[11] S. Eleftheriadis, P. Duffour, P. Greening, J. James, B. Stephenson, and D. Mumovic, "Investigating relationships between cost and CO_2 emissions in reinforced concrete structures using a BIM-based design optimisation approach," *Energy and Buildings*, vol. 166, pp. 330–346, 2018.

[12] P. Sanguinetti, S. Abdelmohsen, J. Lee, J. Lee, H. Sheward, and C. Eastman, "General system architecture for BIM: an integrated approach for design and analysis," *Advanced Engineering Informatics*, vol. 26, no. 2, pp. 317–333, 2012.

[13] U. Vitiello, V. Ciotta, A. Salzan, D. Asprone, G. Manfredi, and E. Consenza, "BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings," *Automation in Construction*, vol. 98, pp. 90–101, 2019.

[14] D. Zuppa, R. R. A. Issa, and P. C. Suermann, "BIM's impact on the success measures of construction projects," in *Proceedings of International Workshop on Computing in Civil Engineering 2009*, pp. 503–512, Austin, TX, USA, June 2009.

[15] BIM Forum Chile, *Initial Guide to Implement BIM in Organizations*, BIM Forum Chile, Santiago de Chile, Chile, 2017, in Spanish.

[16] R. F. Herrera, F. Muñoz, C. Vargas, and M. Antio, "Use and impact of nD models as a tool for project management in the architecture, engineering and construction industry," *Información Tecnológica*, vol. 28, no. 4, pp. 169–178, 2017, in Spanish.

[17] C. M. Eastman, Y. Jeong, R. Sacks, and I. Kaner, "Exchange model and exchange object concepts for implementation of national BIM standards," *Journal of Computing in Civil Engineering*, vol. 24, no. 1, pp. 25–34, 2010.

[18] S. P. Ho, H. P. Tserng, and S. H. Jan, "Enhancing knowledge sharing management using BIM technology in construction," *The Scientific World Journal*, vol. 2013, Article ID 170498, 10 pages, 2013.

[19] D. J. Harrington, "BIM implementation standards at the firm level," in *Proeedings of Structural Congress ASCE*, pp. 1645–1651, EEUU, Orlando, FL, USA, May 2010.

[20] Z. Pezeshki and S. A. S. Ivari, "Applications of BIM: a brief review and future outline," *Archives of Computational Methods in Engineering*, vol. 25, no. 2, pp. 273–312, 2016.

[21] Z. Xu, T. Huang, B. Li, H. Li, and Q. Li, "Developing an IFC-based database for construction quality evaluation," *Advances in Civil Engineering*, vol. 2018, Article ID 3946051, 22 pages, 2018.

[22] BIM committee UK, *AEC (UK) BIM Technology Protocol*, BIM committee UK, High Wycombe, UK, 2015.

[23] Penn State University, *Project Execution Planning guide*, Penn State University, State College, PA, USA, 2011.

[24] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley & Sons, Hoboken, NJ, USA, 2nd edition, 2011.

[25] P. Coates, Y. Arayici, K. Koskela, M. Kagioglou, C. Usher, and O. Reilly, "The key performance indicators of the BIM implementation process," in *Proceedings of the International Conference on Computing in Civil and Building Engineering (ICCCBE'10)*, Nottingham, UK, June-July 2010.

[26] T. Hartmann, H. van Meerveld, N. Vossebeld, and A. Adriaanse, "Aligning building information model tools and construction management methods," *Automation in Construction*, vol. 22, pp. 605–613, 2012.

[27] D. Migilinskas, V. Popov, V. Juocevicius, and L. Ustinovichius, "The benefits, obstacles and problems of practical BIM implementation," *Procedia Engineering*, vol. 57, pp. 767–774, 2013.

[28] A. Tomek and P. Matějka, "The impact of BIM on risk management as an argument for its implementation in a construction Company," *Procedia Engineering*, vol. 85, pp. 501–509, 2014.

[29] M. Tveit and K. Gjerde, "Using building information modelling for planning a high-speed rail project in Norway," *Proceedings of the Institution of Civil Engineers-Civil Engineering*, vol. 171, no. 3, pp. 121–128, 2018.

[30] F. Meng, T. Shi, and B. Liu, "Research on BIM application in high-speed railway OSC operation maintenance management," in *Proceedings of the 3rd International Conference on Electrical and Information Technologies for Rail Transportation (EITRT 2017)*, vol. 483, pp. 853–860, Changsha, China, October 2017.

[31] Building Information Council–BIR, *BIR Leaflet Number 3 BIM Roles and Competences*, Building Information Council, Rotterdam, Netherlands, 2015, https://www.bouwinformatieraad.nl/main.php?mode=download_cat&cat_id=9.

[32] S. Eleftheriadis, D. Mumovic, P. Greening, and A. Chronis, "BIM enabled optimisation optimisation framework for environmentally responsible and structurally efficient design systems," in *Proceedings of the 32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future*, Oulu, Finland, June 2015.

[33] F. Hevia, "Required hardware for revit," 2012, in Spanish, https://bimchile.wordpress.com.

[34] A. Sánchez, "System requirements and recommendations for REVIT®," 2016, in Spanish, https://www.espaciobim.com.

[35] D. Wang, J. Fan, H. Fu, and B. Zhang, "Research on optimization of big data construction engineering quality management based on RNN-LSTM," *Complexity*, vol. 2018, Article ID 9691868, 16 pages, 2018.

[36] R. A. Kivits and C. Furneaux, "BIM: enabling sustainability and asset management through knowledge management," *The Scientific World Journal*, vol. 2013, Article ID 983721, 14 pages, 2013.

[37] E. Focael, "Optimization of the bidding process of public constructions, through the use of discreet events simulation and building information modeling, under an environment of extreme collaboration," Proyecto FONDECIT Regular, 2017, in Spanish.

[38] Plan BIM Comité de transformación Digital CORFO, *BIM Roles and BIM Roles Matrix*, CORFO, Santiago, Chile, 2017, in Spanish.

[39] C. Boton and D. Forgues, "Practices and processes in BIM projects: an exploratory case study," *Advances in Civil Engineering*, vol. 2018, Article ID 7259659, 12 pages, 2018.

[40] M. Stelzer, N. Radoncic, P. L. Iserte Llacer, A. Tatar, and M. Holmberg, "BIM processes and workflows using the example of the subway extension in Stockholm," *Geomechanics and Tunnelling*, vol. 11, no. 4, pp. 340–347, 2018.

[41] B. Succar, "The BIM maturity index," 2015, in Spanish, http://www.bimthinkspace.com.

[42] UK Government Strategy Task Group, *AEC (UK) BIM Technology Protocol, Version 2.1.1*, UK Government Strategy Task Group, UK, 2015, https://aecuk.files.wordpress.com/2015/06/aecukbimtechnologyprotocol-v2-1-1-201506022.pdf.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 7402089, 13 pages
https://doi.org/10.1155/2019/7402089

Research Article

Automated Conversion of Building Information Modeling (BIM) Geometry Data for Window Thermal Performance Simulation

Changmin Kim, [1] **Changyoung Park**, [1] **Changho Choi**, [2] **and Hyangin Jang** [1]

[1] *Institute of Green Building and New Technology, Mirae Environment Plan Architects, Seoul 01905, Republic of Korea*
[2] *Department of Architectural Engineering, Kwangwoon University, Seoul 01897, Republic of Korea*

Correspondence should be addressed to Hyangin Jang; hijang@mrplan.co.kr

Received 26 November 2018; Revised 15 January 2019; Accepted 23 January 2019; Published 17 February 2019

Guest Editor: Eugenio Pellicer

A window set is defined as a window where the frame and the glass are combined and is used at the part that comes into contact with the air. As the performance evaluation of window sets has gained significance, the need for software that can simulate window set performance has also increased accordingly. However, the simulation of window sets is not carried out efficiently due to the difficulty in the window set modeling. Meanwhile, the design of building information modeling has recently proliferated so that the window set BIM library is distributed online. If such a window set BIM library is utilized in the window set simulation, it is expected that the productivity issue that occurs in the simulation process could be improved. Therefore, this study proposes a method to automatically convert the information required in the simulation of the window set heat transfer coefficient from the BIM. In order to achieve the purpose of this study, the following procedure is carried out. First, the framework for converting the information required in the simulation of the window set heat transfer coefficient from the BIM is suggested. Second, the method to extract and convert BIM data based on the suggested framework is proposed. Lastly, the BIM data conversion program is developed, and its performance is validated by applying the window set BIM case. The case study result showed that the information converted and entered from the window set data BIM conversion program coincided with the information entered in the window set BIM. It is expected that the result of this study will increase the productivity of window set simulations, which will lead to the increased use of certification through these simulations.

1. Introduction

Since the performance evaluation of window sets has gained significance, the need for software that can simulate window thermal performance has also increased accordingly. In the case of applying an evaluation method through a test, costly testing equipment is necessary for measuring the heat transfer coefficient of window sets. However, a simulation can evaluate the thermal performance of a window set without the need for separate testing equipment. Also, data indicating small changes, which cannot be determined due to uncertainties that occur in the evaluation method through a test, can be obtained from the simulation [1]. In addition, the effect of input variables related to the heat transfer coefficient of the window set can be determined [2]. In particular, the determined information can be utilized in the design process for achieving the target performance of the window set by a manufacturer [1]. As the burden of expenses and time required for the certification of window sets can be reduced, the window set simulation has been introduced and implemented in various countries, including the United States and the Republic of Korea.

However, the window set simulation is not efficiently applied despite its various advantages. In many studies, inconvenient user interfaces of window set simulation programs and difficulty in window set modeling are cited as examples of some obstacles [3, 4]. In fact, the user should draw each edge of all window set members for window set modeling. The user should also specify each material composing the respective window set member, select an edge inside and outside the window set, and specify the boundary condition. Although the modeling time varies by program, window set modeling takes approximately one hour to complete [5]. Therefore, it is essential to develop a method that can automatically provide modeling information required by the window set simulation program in order to maximize the window set simulation.

Meanwhile, the use of the building information modeling (BIM) design is currently proliferating in the construction industry [6]. Along with the BIM design, the establishment of a library for the BIM design is being proliferated, and window set manufacturers are already making the window set BIM library accessible online. If such a window set BIM library is utilized in a window set simulation, it is expected that the productivity issue that occurs in the simulation process could be improved. Therefore, this study proposes the method to automatically convert the information required in the window set simulation from the BIM.

In order to achieve the purpose of this study, the following procedure is carried out. First, the framework for converting the information required in the simulation of the window set from the BIM is suggested. Second, the method to extract and convert BIM data based on the suggested framework is proposed. Examples of BIM data for the window set's heat transfer coefficient simulation include the information on the geometry and boundary of the window set. Lastly, the BIM data conversion program is developed in consideration of user convenience for the window set's heat transfer coefficient simulation, and the performance of the developed program is verified by applying the window set BIM case.

2. Literature Review

The Industrial Foundation Classes (IFC) data model is the standardized method to save information included in BIM. IFC includes the geometry and semantic information of the members composing a building as well as the exchange of information that is available during the building's life cycle [7, 8]. Also, the information included in BIM can be utilized without specific BIM software [9]. Due to such advantages, IFC is widely utilized in various fields, including building energy simulation [6], construction quality evaluation [10], and progress measurement [11]. Some studies for mapping the information included in the IFC to another file format as required by an application are being carried out based on the field of 3D geographic information system.

In the field of 3D geographic information system, many studies for mapping an IFC file into the CityGML format have been carried out. Typical studies that were recently conducted were summarized in this study. Cheng et al. [12] suggested a method for mapping an entity included in the IFC and an entity in the format of CityGML to each other. For such purpose, the relationship between entities was discovered by applying the text-mining method to the name and definition of the entity in the IFC and CityGML. Donkers et al. [13] suggested a method for automatically converting the property information and geometric information included in the IFC into CityGML. For such purpose, relevant entities for each format were defined in advance according to the data structure, and the geometric transformation of the building envelope was carried out according to the information required by CityGML. Deng et al. [14] suggested a framework for the bidirectional mapping between the IFC and CityGML. The mapping rule between the IFC and CityGML was created by applying the instance-based method in order to enable the bidirectional mapping between the IFC and CityGML. Stouffs et al. [15] suggested a method for defining the entity relationship between the IFC and CityGML to be applicable to various cases. For such purpose, the entity relationship was defined by applying the triple graph grammars.

Apart from the studies regarding the conversion of an IFC file into CityGML, other related studies have been carried in other fields. Kim et al. [16] suggested a method for converting an IFC file into an IDF file which was the format supported by EnergyPlus, a building energy simulation program. Also, Kim et al. [17] suggested a method for converting an IFC file into an INP file which was utilized in the DOE-2-based building energy analysis.

In order to map the information included in the IFC to a file in a format required by each application, it is necessary to carry out the process to analyze the data structure of two different formats and to convert and map the relevant entities in order to match the value and representations [12]. Such studies presented the possibility that an IFC file in building units could be converted into and utilized in an appropriate format for each application. However, the conversion in building units was mainly carried out in previous studies. Since the conversion in building units is the methodology based on a simple geometry, the previously suggested building unit method is not appropriate for the window simulation, which requires detailed geometry information. Moreover, studies for converting the information included in the BIM into an appropriate format for the window set simulation have not yet been carried out within the scope of the author's understanding. Therefore, a method for converting the detailed geometry information included in the BIM into an appropriate format for the window set simulation is proposed in this study.

3. BIM Data Conversion Method for Window Set Simulation

THERM is the program developed by the Lawrence Berkeley National Laboratory (LBNL), and it simulates the 2D heat transfer of the window set. In previous studies, experiment results showed that the THERM's simulation result was sufficiently accurate when compared with the evaluation method through test [18, 19]. Moreover, THERM is approved by the National Fenestration Rating Council (NFRC) of the United States. This program has been certified and utilized for the performance evaluation and grade assessment of the window set in various countries, including the U.S. and the Republic of Korea. As THERM is particularly easy to use in comparison with other 2D heat transfer simulation programs and requires less time for users to learn, it is widely used [20]. Therefore, THERM, which is the representative program for simulating the thermal performance of the window set, is highlighted as this study is conducted. The file formats supported by THERM include THM and THMX, and the information included in these two file formats is identical. THM is THERM's own unique format, which is not an open format. On the other hand, THMX is the XML (Extensible Markup Language) format, which is simple to use for file creation and modification. Therefore, this study suggests the framework to extract the window set BIM information saved to IFC and to convert and output such information into a THMX file supported by THERM. The framework suggested in this study is shown in Figure 1.

First, the geometry data are extracted from the window set BIM. The step that takes the longest time in the modeling process for the window set simulation is window set modeling. Modeling includes the generation of a cross-section and a boundary as well as the setting of the boundary condition. The geometry data of the window set are necessary for the generation of the cross-section and boundary of the window set as well as the setting of the boundary condition. Therefore, the method to extract data regarding the geometry of the members that compose the window set from the BIM is proposed.

Second, the data extracted from the window set BIM are converted into data that are required for the window set heat transfer coefficient simulation. The geometry of the window set is expressed according to the IFC's geometry representations. However, the geometry of a member that composes the window set is defined as a set of outside vertices in the window set simulation program. Therefore, the complicated geometry of the frames that compose the window set changes to a set of outside vertices. Next, the 3D geometry extracted from the BIM is converted into 2D cross-sections, such as the head, sill, and the jamb, all of which are required by the window set simulation program. Additionally, the outline of the window set is extracted and converted into information regarding the boundary condition based on the converted cross-sections.

Third, the converted information is outputted in a format that can be inputted to the window set simulation program. A unique format that can be inputted to the window set simulation program has been specified. The information regarding the geometry and boundary of the window set is outputted automatically in a format that can be inputted in the THERM, according to the method proposed in this study.

3.1. Geometry Data Extraction from BIM. The BIM expresses the geometry of an object as a plane or a solid, which is a set of a number of planes [21]. It is determined in various expression methods, including "Body SweptSolid," "Body Brep (Boundary Representation)," and "Body CSG (Constructive Solid Geometry)" in IFC according to the geometry of the object [22]. In the case of the window set, a simple geometry such as a wood frame and glass as well as a complicated shape exists. In the IFC file, a simple geometry of the window set is expressed in the "Body SweptSolid Geometry" method. However, a complicated geometry of the window set is expressed in the "Body Brep Geometry" method [13]. As the method to extract data on a simple geometry has been discussed in previous studies [23], this study will primarily focus on and discuss the method to extract complicated geometry data from the IFC file.

Figure 2 shows the process to extract geometry data in "Brep" format. For the geometry data in the IFC, the coordinate in the local coordinate system can be extracted after converting it to the global coordinate system [14]. While the method to extract a coordinate in the local coordinate system from an IFC file varies for each geometry expression method, the information of the "Brep" geometry in the IFC is expressed as shown in Figure 2. IfcWindowStyle is an entity that defines the style of the window set and includes the geometry data. IfcRepresentationMap and IfcShapeRepresentation can be referred from IfcWindowStyle sequentially, and the IfcShapeRepresentation entity includes information showing whether the geometry type of the relevant object is "SweptSolid" or "Brep." If the geometry type in IfcShapeRepresentation is "Brep," IfcFacetedBrep can be referred from IfcShapeRepresentation, and IfcFacetedBrep includes the list of separate members that compose the window set. The list of faces composing each member can be checked from IfcClosedShell, and IfcClosedShell includes some IfcFace information. IfcFace has a polygonal geometry, and the coordinate of vertices composing each face can be extracted from IfcCartesianPoint. It is possible to extract the geometry data of the window set saved in the "Brep" method by extracting the coordinate of vertices of all faces composing the window set.

3.2. Data Conversion

3.2.1. Simplification of Window Set Geometry. A more complicated geometry is expressed as a larger number of faces in the design tool [24]. In order to utilize a model that has such a complicated geometry in the simulation, the simplification of the model should first be conducted [25]. The top drawing in Figure 3 indicates the frame that composes the window expressed with a number of faces. For the first triangle, the edges that compose the outline of the member are the edges shown in green as shown in the figure. As the red edge is not an edge that composes the outline of the member, it should be removed. Unlike the edges in green, the first and second triangles share the red edge. From the understanding of this information, this study suggests the simplification method to decimate an edge that is shared with an adjacent triangle among the edges composing the triangle.

To achieve this purpose, the following is carried out. First, the three vertices composing the triangle are converted into three edges, including two vertices for all the triangles that compose the shape of the member. Second, a triangle for simplification is selected arbitrarily. Third, all the triangles that compose the figure are checked to determine whether a triangle that includes the same edge among the three edges

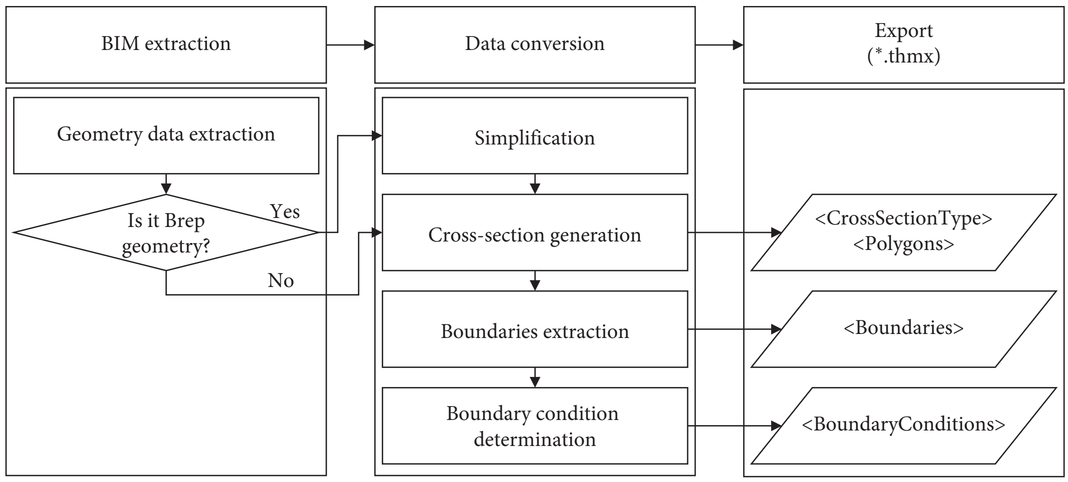


Figure 1: BIM-based framework for window thermal performance simulation.

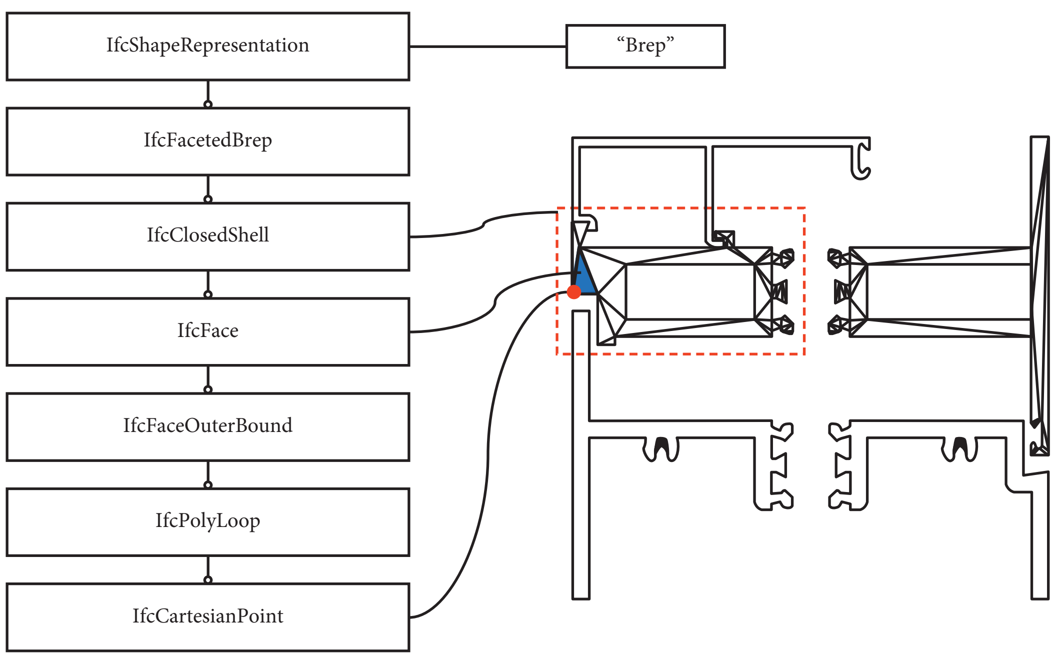


Figure 2: Data structure of "Body Brep Geometry" in IFC.

that compose the selected triangle exists. If the triangle that includes the same edge exists, the vertices that compose all the other edges, except for the relevant edge, are saved. When this process is completed, an edge that overlaps with the other triangles will be removed. Next, it is possible to remove an edge inside the figure and extract the coordinate of vertices composing the outline of the member sequentially by repeating the above process for a triangle that shares the vertex composing the triangle as the next triangle.

3.2.2. Cross-Section Generation. As mentioned above, THERM is the 2D-based simulation program. In THERM, a 2D cross-section is defined as head, jamb, or meeting rail according to its position [26]. In this study, the position of the glass is utilized in order to define the cut position according to the required cross-section. According to the cross-section of each member that should be extracted based on the glass, the members located at the top can be classified as the head, the members located at the bottom can be classified as the sill, and the members located on the left or right can be classified as the jamb.

The first step for utilizing the coordinate information of the glass is to classify between the glass and the frame among the members composing the window set. In the case of the window set, the glass is thinner than the frame. Therefore, a member, which is the thinnest among the members of the window set, is classified as the glass, and other members are classified as the frames.

The cross-section according to the window set type is created based on the glass that was previously classified. Figure 4 shows an example of the cross-section generation of

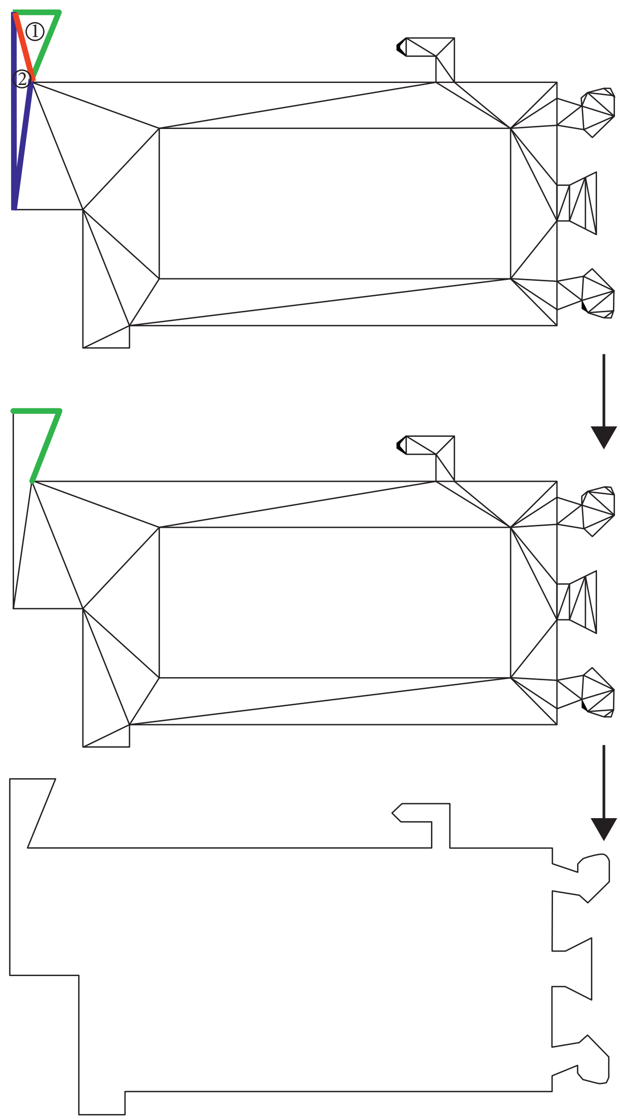


Figure 3: Geometry simplification algorithm.

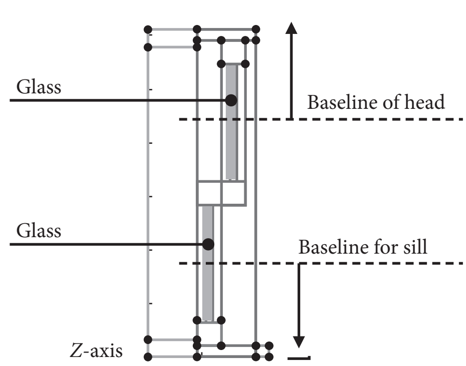


Figure 4: Cross-section generation algorithm (head and sill).

the head and the sill. As shown in the figure, a vertex, which is the coordinate of Z that is larger than the coordinate of Z based on the glass, is extracted for the head based on the profile. On the other hand, a vertex, which is the coordinate of Z that is smaller than the coordinate of Z based on the glass, is extracted for the sill based on the profile. In this way, a vertex, which is the coordinate of X that is larger than the coordinate of X based on the glass, is extracted for the jamb. For the meeting rail, all vertices existing between two windows are extracted as shown in Figure 5. The coordinate of the vertex that shows the geometry for the 2D cross-section of the head, sill, jamb, and the meeting rail can be extracted from the 3D geometry information extracted from the IFC file through this process.

3.2.3. Boundary Extraction. In the window set simulation, the boundary condition defines the temperature and the surface heat transfer coefficient of each member. For the window set simulation, the exterior and interior surfaces of the cross-section of the window set are specified as different boundary conditions to each other. The window set BIM includes the geometry information of each member. However, the information regarding the boundary of the window set is not included. Therefore, the method to extract only the geometry of the boundary of the window set among the geometry information of the window set and to specify the boundary condition of the relevant geometry is necessary for extracting the boundary condition of the window set.

In this study, the following method is applied in order to extract only a geometry corresponding to the boundary among the geometry information of a member that composes the window set. First, the geometry information of all members that compose the window set is extracted. Second, all the coordinates that correspond to the vertex of each member are determined. Third, the top, or the start point of the window set, is connected to the next vertex that composes the figure. In the case of an intersection, the movement in the direction of the window is the priority. The second priority is to connect the vertex in the bottom direction (Figure 6).

3.2.4. Boundary Condition Determination. The coordinate information of edges composing the boundary of the window set is extracted, and the boundary condition of each edge is matched. In the window set simulation, the boundary condition is classified as “Outside,” “Inside,” or “Adiabatic.” Interior indicates the inside boundary, Exterior indicates the outside boundary, and Adiabatic indicates the insulation boundary with no heat transfer. The direction of the window set is initially extracted from the IFC file to differentiate between the interior and exterior boundaries. In the IFC, the direction of the object is included in the IfcDirection entity [27]. Therefore, it is possible to confirm the direction of the window set by extracting the information included in IfcDirection, which is connected to IfcWindow. If the interior is south and the exterior is north in the IFC, IfcDirection does not exist. However, the values for the other directions are included. The interior and exterior directions, according to the direction information of the window set extracted from IfcDirection, are shown in Table 1. The interior side is set as the interior and the exterior side is set as the exterior for boundary condition according to the direction information among the edges composing the boundary that was extracted above. Next, the edges that are not in the

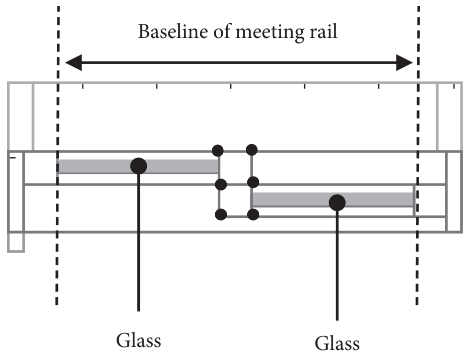


Figure 5: Cross-section generation algorithm (meeting rail).

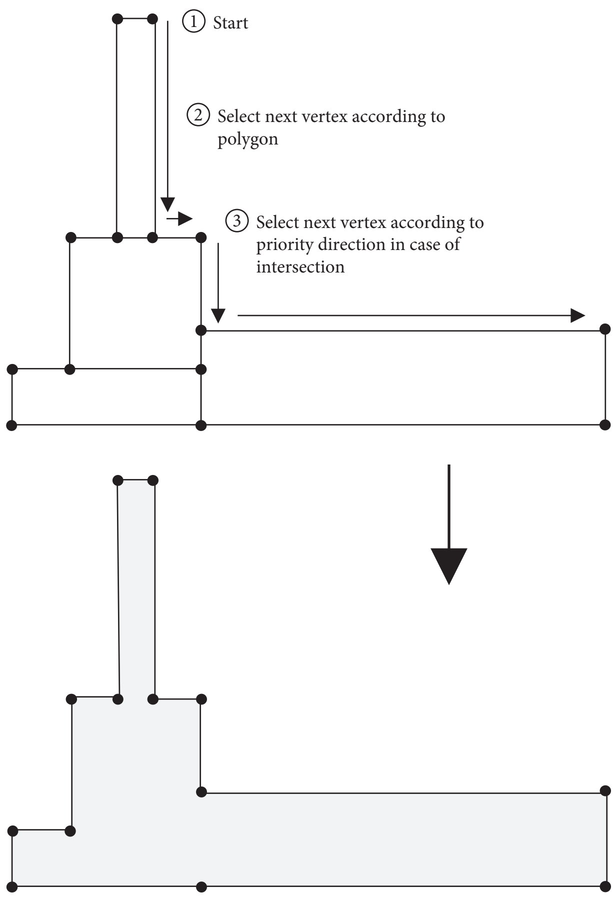


Figure 6: Boundary extraction process.

interior and exterior directions are set as "Adiabatic," which is the adiabatic boundary side for the boundary condition.

3.3. Export. The geometry and boundary condition extracted from the IFC file can be extracted as the relationship between specific entities. However, there is a difference between the format of the information extracted from the IFC file and the format required in THMX that is compatible with THERM. Therefore, it is necessary to convert each type of information extracted from IFC into the format that is required in THMX.

Table 1: Boundary condition determination by IfcDirection.

IfcDirection	Boundary condition
N/A	Interior (top) / Window set / Exterior (bottom); compass N, E, S, W
IfcDirection (−1, 0, 0)	Exterior (top) / Window set / Interior (bottom); compass N, E, S, W
IfcDirection (0, 1, 0)	Interior (left) / Window set / Exterior (right); compass N, E, S, W
IfcDirection (0, −0, 0)	Exterior (left) / Window set / Interior (right); compass N, E, S, W

In this study, the geometry information extracted from IFC was converted into the format that was required in THMX. The result through the cross-section generation algorithm that is converted into <CrossSectionType>, which is the cross-sectional type and a proper format for <Polygons>, which indicates the 2D geometry of the cross-section, is inputted to THMX. Here, the cross-sectional types including the sill, head, and the meeting rail are inputted as the cross-sectional type. For the boundary information in THMX, the information on the two vertices and property should be entered for each edge composing the boundary. For the geometry information in the boundary information, each vertex is connected and arranged in a way in which the starting point is connected to the endpoint. Then, this information is saved in the <Boundaries> class of THMX. In addition, the boundary information that corresponds to the Exterior, Interior, and Adiabatic classifications, as previously determined, is also saved together. The entity items extracted from IFC and the items of the result converted through the method suggested in this study that is outputted to THMX are shown in Table 2.

4. Case Study

The BIM data conversion program for the simulation of the window set heat transfer coefficient that was developed in this study can be used easily by the general public. Moreover, it is developed to facilitate the management of a material

Table 2: Mapping from IFC to THMX.

IFC entity	Conversion data	THMX class	
IfcWindowStyle	Cross-section generation results	<CrossSectionType>	Cross-sectional type
	Boundary condition determination results	<BoundaryCondition>	Boundary condition name
	Cross-section generation results	<Polygons>	Point index
	Cross-section generation results		Nsides
	Boundary condition extraction results	<Boundaries>	BC polygon ID
	Boundary condition extraction results		Boundary condition
	Boundary condition extraction results		Polygon ID
	Boundary condition extraction results		Point index

database. In case of a material database, the program is designed to allow the user to utilize the basic database and update the data for a newly developed material. The home item includes the function to import an IFC file and export the extracted information in the THMX format. The library item includes the function to manage the database content related to glass and frame material. The default screen of the developed program is shown in Figure 7.

In order to verify the performance of the BIM data automatic extraction program developed in this study, the extraction result targeting the window set BIM was evaluated. The window set with a simple cross-section expressed as ‘Body SweptSolid Geometry’ and the window set with a complicated cross-section expressed as “Body Brep Geometry” were selected as the targets for the case evaluation. Also, the double-hung windows and casement windows are specific types of windows that are mainly used in residential buildings. Therefore, the double-hung windows expressed as “Body SweptSolid Geometry” and the casement windows expressed as “Body Brep Geometry” were selected as the targets for the case study in this study. The default libraries provided by Autodesk® Revit® and the window set BIM library accessible on the Internet were utilized as the window set BIM for the case evaluation. The window set BIM was modeled through the family creation, and the material and finishing materials of each member were specified as family parameters in order to connect the material of each member composing the window set.

4.1. Test Case 1. The first window set case for verifying the suggested method is shown in Figure 8. This is the double-hung window in a wood frame that has the cross-section of a simple shape. The modeling of the window set BIM was carried out in Autodesk® Revit® and was saved to an IFC file format. The following is carried out for test case 1. First, the operational feasibility of the window set BIM conversion program developed in this study was verified. In order to verify the operation of the window set conversion BIM program, the IFC file is imported to the program and the type of the cross-section is specified. Second, whether the geometry information and the boundary condition that are “Body SweptSolid Geometry” are outputted correctly to THMX is verified. In order to verify the status of the output to THMX, the THMX file outputted in the window set BIM conversion program is analyzed to determine if it is outputted properly for the THMX format. Lastly, whether the information outputted to THMX can be imported to the THERM program is verified. To achieve this purpose, the THMX file outputted in the window set BIM conversion program is imported to THERM and the information on the geometry and boundary is checked from the inputted information.

The window set BIM saved in the form of an IFC file can be imported to the program developed in this study. The program developed in this study imports an IFC file and simultaneously recognizes the type of window. Moreover, it provides an option to select a cross-section that is suitable for the window type. When the user selects a cross-section, the program provides the type of the proper cross-section corresponding to the middle window. In the case of a double-hung window, which is the first test case, the head, upper jamb, lower jamb, meeting rail, and the sill can be selected as the type of cross-section. Figure 9 shows the result of importing an IFC file to the window set BIM conversion program developed in this study and the head selection as the cross-section. As shown in the figure, the geometry of the cross-section is outputted at the center of the program GUI. It was confirmed that the outputted geometry information was the same as the cross-section of the head in test case 1. The user can output the geometry and boundary information as a THMX file by selecting the type of cross-section and pressing the Save THMX button.

Figure 10 shows the THMX file of the head cross-section outputted in the window set BIM conversion program. We can see that the <Polygons> class includes the geometry information of the window set, and the x coordinate and y coordinate of the members composing the cross-section of the member according to <Point index> are saved. This means that the geometry information previously saved in the IFC file has been properly converted into the form that is required in the THMX file. In addition, “Adiabatic,” “KS Interior,” and “KS Exterior” have been specified for the boundary condition in the <Boundaries> class, and the point index of the relevant boundary is saved.

A file saved by THMX can be imported directly from THERM. Figure 11 shows the result of importing a THMX file that includes the cross-section information of the head outputted using the program developed in this study from THERM. We can see from the figure that the geometry information, whose cross-sectional type is a head, is imported to THERM and is the same as the geometry of the cross-section shown in Figure 9. In Figure 10, the green border that surrounds the geometry of the cross-section indicates the boundary of the cross-section. We can see that the boundary of the cross-section is outputted through the

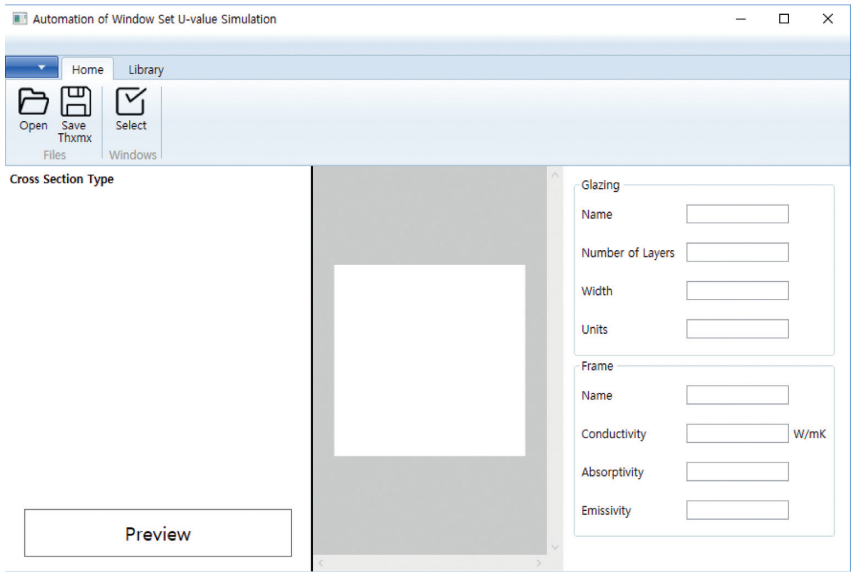


Figure 7: Graphic user interface of the developed program.

Figure 8: BIM model of test case 1.

suggested method without configuring additional settings by the user. We can also see that when the boundary corresponding to the outside among the boundaries of the window set is selected, "KS Exterior" is entered. The type of the boundary is also automatically converted and outputted in BIM through the suggested method.

4.2. Test Case 2. The second window set case for verifying the suggested method is shown in Figure 12. The window type in test case 2 is the casement window, and it has the cross-section of a complicated geometry. test case 2 was targeted to verify whether the geometry information, which is "Body Brep Geometry," has been correctly outputted as the cross-section. To achieve this purpose, the head and the meeting rail were selected among the cross-sectional types of the window set and converted into a THMX file. Then, the THMX file outputted from the program was imported to THERM. Just as in the procedure described in test case 1, the modeling of the window set BIM was conducted in Autodesk® Revit® and was saved to an IFC file format.

The cross-section created through the method suggested in this study is shown in Figures 13 and 14. Figure 13 shows the head among various cross-sections, and Figure 14 shows the cross-section of the meeting rail. We can see from the result that the complicated geometry of the window set, which was converted into a 2D cross-section, was imported to THERM. We can see from the THERM input result figure below that the geometry information, expressed as "Body Brep Representation," has been simplified through the conversion method suggested in this study. It was also observed that the information was outputted properly in a form required in the THMX file. This indicates that the window set BIM with a simple geometry, as well as a complicated geometry, can be converted into a proper geometry for the simulation program of the window set's heat transfer coefficient in the future.

5. Discussion

The window set modeling process for simulating the heat transfer coefficient of the window set is labor-intensive due to an inconvenient user interface. Therefore, its utilization is limited regardless of the various advantages of the simulation. As the BIM design has recently been revitalized, various window set manufacturers have released the BIM libraries online. If such BIM libraries are converted and utilized for the window set simulation, the manpower required in the modeling process for the window set simulation can be reduced. In Section 3, the method to convert BIM data for the window set simulation suggested in this study was described. In Section 4, the result of the case study was illustrated. The result of the case study indicates that the method suggested in this study has the following benefits.

First, the method for extracting the Brep shape that indicates the detailed geometry of a member, not the

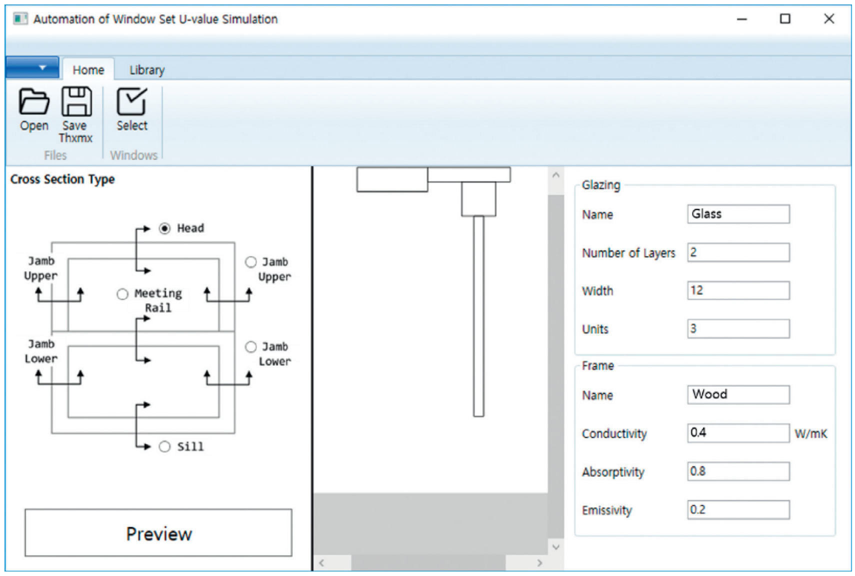


Figure 9: Conversion program input result of test case 1.

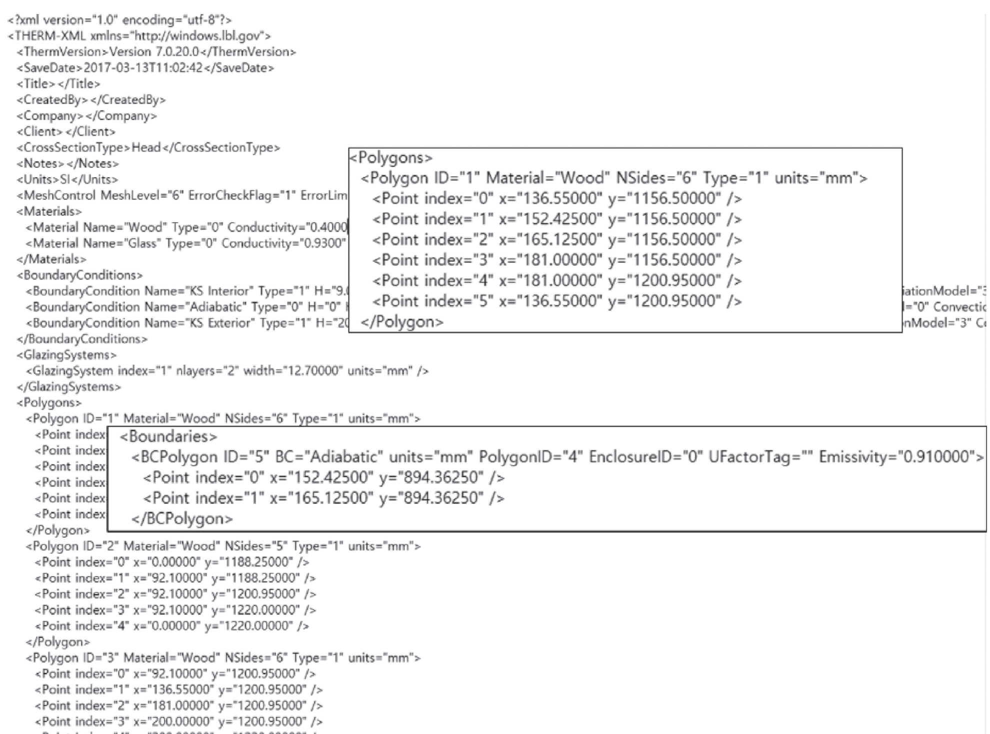


Figure 10: THMX output result of test case 1.

geometry information of CSG and swept solid expressed mainly, which in case the previous building BIM, was suggested. The method for converting the extracted geometry information into an appropriate format for window simulation was also suggested. This has a significance as the basic study on the method to express the geometry information of the IFC. Moreover, the suggested model can be utilized in the extraction of the geometry information from other separate members that have a complicated geometry in the future in addition to that of the window set.

Second, the geometry information and the boundary information were converted and entered into the simulation program automatically from the window set BIM through the suggested method as the result of the case study. In order to certify the window set, the modeling should be performed manually in the same way in a certified program based on the window set drawing. As this process accounts for a significant amount of time in the simulation, a window set certification agency can save the manpower required for the certification of a window set by automating such a process. In this way, a

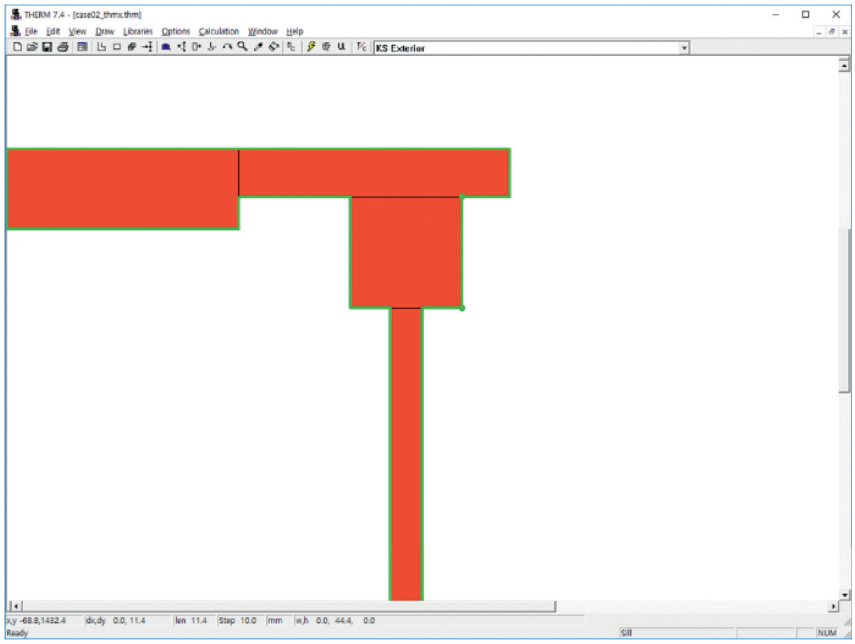


Figure 11: THERM input result of test case 1.

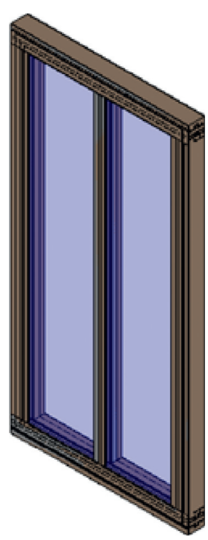


Figure 12: BIM model of test case 2.

window set manufacturer does not require additional manpower to evaluate a change in the certification class according to a change in the geometry of a window set when developing a product to submit for certification.

The BIM data conversion method suggested in this study can enter the geometry and boundary information of a window set to the simulation program automatically. However, the following limitations of this method should be investigated continuously in the future.

First, THERM, which was developed by LBNL, was selected as the target in this study among window set simulation programs. In the future, a method applicable to other window set simulation programs in addition to THERM will be suggested.

Second, a study related to the conversion of geometry and boundary information, which took the largest amount of time, was carried out in this study. However, the material information of the members composing a window set is also required for the simulation. Therefore, a method to identify the property information of materials through the establishment of a database will be suggested in the future.

6. Conclusions

There is a growing interest in the performance of the window set along with a growing interest in the improvement of energy efficiency in buildings. Therefore, a method for evaluating the performance of a window set is also gaining significance. The performance evaluation of a window set through simulation is highly practical as expensive equipment is not required. However, its utilization is limited due to the limitation of labor-intensive window set modeling. Therefore, a study for extracting the information required for window set modeling from BIM and converting the data into an appropriate format for THERM, a window set simulation program developed by LBNL, was carried out in this study.

This study suggested the method to automatically extract, convert, and output the information on the geometry and boundary required in the window set's heat transfer coefficient simulation from the window set BIM. To achieve this purpose, the method to extract the geometry information from the window set BIM saved as an IFC file, which was the standard format of BIM, was suggested. Since the window set is expressed as complicated geometry information, the method to extract "Body Brep Representation," which was not previously suggested, is included. Second, the method to convert the geometry information extracted from the window set BIM into the geometry of the cross-section, geometry of the boundary, and the boundary

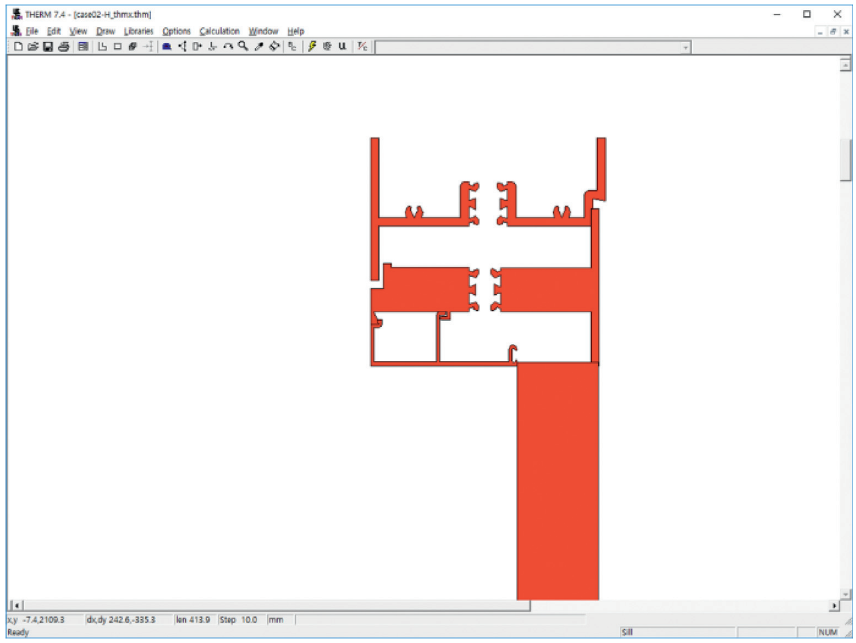


Figure 13: THERM input result (head) of test case 2.

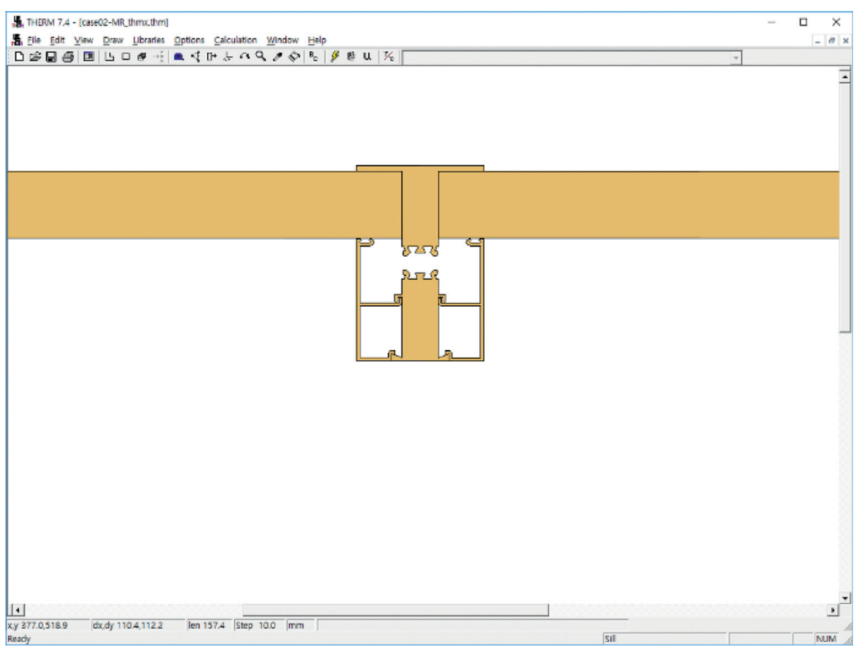


Figure 14: THERM input result (meeting rail) of test case 2.

type was suggested. The geometry information was simplified, and the cross-section was created in order to convert it into the geometry information of the cross-section required in the window set simulation. The boundary was also extracted based on the priority in order to convert the geometry information of the window set into the boundary information, and the boundary condition was determined based on the direction of the window set. Lastly, the window set BIM conversion program that took in consideration the user convenience based on the suggested method was developed, and its performance was verified by applying the window set BIM model to the developed program. The information on the geometry and property was extracted by applying the selected window set case to the program, and this information was converted to a THMX file. It was confirmed that the converted information inputted to THMX could be imported to THERM and that the converted geometry and boundary information was inputted.

Since the information on the geometry and boundary required in the window set's heat transfer coefficient simulation can be inputted automatically through the program developed in this study, the manpower and time required for the simulation can be reduced. It is expected that the program can be particularly useful in the window set design step to evaluate the performance repeatedly by changing the shape of some members. In conclusion, it is expected that the increased productivity of the window set simulation will lead to the increased use of certification through the window set simulation. The performance of the developed program was verified in this study based on the analysis of some cases.

This study targeted THERM, which was developed by LBNL among window set simulation programs. This study has a limitation, in which only the geometry and boundary information was converted. A method that can be applicable to other window set simulation programs in addition to THERM and a method to automatically extract the property information of the material from the IFC will be suggested in the future.

THERM, the window set simulation program that was developed by LBNL and discussed in this study, can be downloaded from https://windows.lbl.gov/software/therm.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Institute for Information and Communications Technology Promotion (IITP) grant funded by the Korean government (MSIT) (no. 2018-0-01074, Development of Automatic Building Information Modelling of Existing Building Based on Videogrammetry) and Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (no. 2018R1D1A1B07041890).

References

[1] D. Arasteh, E. Finlayson, J. Huang, and C. Huizenga, "State-of-the-art software for window energy-efficiency rating and labeling," in *Proceedings of the ACEEE'98 Summer Study on Energy Efficiency in Buildings*, pp. 1–6, Pacific Grove, CA, USA, August 1998.

[2] A. Sharda and S. Kumar, "Statistical evaluation of U-value of a window with inter-pane blinds," *International Journal of Ambient Energy*, vol. 37, no. 4, pp. 384–397, 2014.

[3] J. Zajas and P. Heiselberg, "Parametric study and multi objective optimization of window frame geometry," *Building Simulation*, vol. 7, no. 6, pp. 579–593, 2014.

[4] M. de Gastines, A. Villalba, and A. Pattini, "Improved model for the thermal performance calculation of non-planar window frames for building simulation programs," *Journal of Building Performance Simulation*, vol. 9, no. 6, pp. 633–647, 2016.

[5] P. Parker and C. Lozinsky, "Thermal and hygrothermal analysis in building envelope commissioning," in *Proceedings of the Building Enclosure Science & Technology Conference*, pp. 1–24, Portland, OR, 2010.

[6] K. Lee and S. Choo, "A hierarchy of architectural design elements for energy saving of tower buildings in Korea using green BIM simulation," *Advances in Civil Engineering*, vol. 2018, Article ID 7139196, 13 pages, 2018.

[7] Y.-H. Lin, Y.-S. Liu, G. Gao, X.-G. Han, C.-Y. Lai, and M. Gu, "The IFC-based path planning for 3D indoor spaces," *Advanced Engineering Informatics*, vol. 27, no. 2, pp. 189–205, 2013.

[8] J. Ryu, J. Lee, and J. Choi, "Development of process for interoperability improvement of BIM data for free-form buildings design using the IFC standard," *International Journal of Software Engineering and Its Applications*, vol. 10, no. 2, pp. 127–138, 2016.

[9] Z. Xu, Y. Zhang, and X. Xu, "3D visualization for building information models based upon IFC and WebGL integration," *Multimedia Tools and Applications*, vol. 75, no. 24, pp. 17421–17441, 2016.

[10] Z. Xu, T. Huang, B. Li, H. Li, and Q. Li, "Developing an IFC-based database for construction quality evaluation," *Advances in Civil Engineering*, vol. 2018, Article ID 3946051, 22 pages, 2018.

[11] C. Kim, H. Son, and C. Kim, "Automated construction progress measurement using a 4D building information model and 3D data," *Automation in Construction*, vol. 31, pp. 75–82, 2013.

[12] J. C. P. Cheng, Y. Deng, and C. Anumba, "Mapping BIM schema and 3D GIS schema semi-automatically utilizing linguistic and text mining techniques," *Journal of Information Technology in Construction*, vol. 20, pp. 193–212, 2015.

[13] S. Donkers, H. Ledoux, J. Zhao, and J. Stoter, "Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings," *Transactions in GIS*, vol. 20, no. 4, pp. 547–569, 2015.

[14] Y. Deng, J. C. P. Cheng, and C. Anumba, "Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison," *Automation in Construction*, vol. 67, pp. 1–21, 2016.

[15] R. Stouffs, H. Tauscher, and F. Biljecki, "Achieving complete and near-lossless conversion from IFC to CityGML," *International Journal of Geo-Information*, vol. 7, no. 9, pp. 1–17, 2018.

[16] I. Kim, J. Kim, and J. Seo, "Development of an IFC-based IDF converter for supporting energy performance assessment in the early design phase," *Journal of Asian Architecture and Building Engineering*, vol. 11, no. 2, pp. 313–320, 2018.

[17] H. Kim, Z. Shen, I. Kim, K. Kim, A. Stumpf, and J. Yu, "BIM IFC information mapping to building energy analysis (BEA) model with manually extended material information," *Automation in Construction*, vol. 68, pp. 183–193.

[18] B. Griffith, D. Curcija, D. Turler, and D. K. Arasteh, "Improving computer simulations of heat transfer for projecting fenestration products: using radiation view-factor models," *ASHRAE Transactions*, vol. 104, no. 1, pp. 845–855, 1998.

[19] A. Gustavsen, D. Arasteh, B. P. Jelle, C. Curcija, and C. Kohler, "Developing low-conductance window frames: capabilities and limitations of current window heat transfer design tools - state-of-the-art review," *Journal of Building Physics*, vol. 32, no. 2, pp. 131–153, 2008.

[20] C. Huizenga, D. K. Arasteh, and E. Finlayson, "Teaching students about two-dimensional heat transfer effects in buildings, building members, equipment, and appliances

using THERM 2.0," *ASHRAE Transactions*, vol. 105, no. 1, pp. 1–7, 1999.

[21] S. Kota, J. S. Haberl, M. J. Clayton, and W. Yan, "Building information modeling (BIM)-based daylighting simulation and analysis," *Energy and Buildings*, vol. 81, pp. 391–403, 2014.

[22] L. Ma, R. Sacks, and R. Zeibak-Shini, "Information modeling of earthquake-damaged reinforced concrete structures," *Advanced Engineering Informatics*, vol. 29, no. 3, pp. 396–407, 2015.

[23] C.-Y. Park, C.-M. Kim, H.-I. Jang, and C.-H. Choi, "Automated derivation of building envelope thermal performance based on BIM for building energy analysis," *International Journal of Engineering and Technology*, vol. 8, no. 1-4, pp. 1–12, 2019.

[24] P. Cignoni, C. Montani, and R. Scopigno, "A comparison of mesh simplification algorithms," *Computers & Graphics*, vol. 22, no. 1, pp. 37–54, 1998.

[25] S. Gao, W. Zhao, H. Lin, F. Yang, and X. Chen, "Feature suppression based CAD mesh model simplification," *Computer-Aided Design*, vol. 42, no. 12, pp. 1178–1188, 2010.

[26] Lawrence Berkeley National Laboratory, *THERM 5/WINDOW 5 NFRC Simulation Manual*, Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 2003.

[27] Y. Ji, A. Borrmann, J. Beetz, and M. Obergrießer, "Exchange of parametric bridge models using a neutral data format," *Journal of Computing in Civil Engineering*, vol. 27, no. 6, pp. 593–606, 2013.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 9482350, 14 pages
https://doi.org/10.1155/2019/9482350

Research Article

Critical Challenges for BIM Adoption in Small and Medium-Sized Enterprises: Evidence from China

Pengfei Li ,[1] Shengqin Zheng,[1] Hongyun Si ,[2] and Ke Xu[1]

[1]*School of Management Engineering, Shandong Jianzhu University, Jinan 250101, Shandong, China*
[2]*School of Economics and Management, Tongji University, Shanghai 200092, China*

Correspondence should be addressed to Hongyun Si; sihongyun@tongji.edu.cn

Received 16 November 2018; Revised 19 December 2018; Accepted 5 January 2019; Published 11 February 2019

Guest Editor: Tatjana Vilutiene

Building information modelling (BIM) is a set of technologies that aim to increase interorganisational and cross-disciplinary collaboration in the architecture, engineering, and construction (AEC) industries to promote productivity and the quality of design, construction, and maintenance stages of a building. Studies on BIM adoption in small and medium-sized enterprises (SMEs) have remained an under-represented area. It is necessary to understand the main challenges hindering the adoption of BIM in SMEs and to consider corresponding strategies that can be applied in order to obtain further understanding of BIM in SMEs. On the basis of literature review and interview, stakeholder-associated factors were identified from a network perspective, and the social network analysis (SNA) method was applied to determine the interconnections between the influencing factors and links in BIM adoption in SMEs. Eventually, 10 critical factors and 10 crucial links were selected and divided into six challenges. Corresponding strategies, including cultivating the BIM perception of SMEs, integrated project delivery, strengthening the legal environment for BIM adoption in SMEs, and developing native software and standards and cloud-based technology, were proposed to mitigate these challenges. The strategies may help practitioners gain an in-depth understanding of BIM adoption in SMEs from a stakeholder-oriented perspective.

1. Introduction

Building information modelling (BIM) has been increasingly used by the architecture, engineering, and construction (AEC) industries to address performance problems that have long plagued the construction industry [1, 2]. Using BIM methods, compared with the traditional working model, can help us achieve coordination, cooperation, and integration whilst improving information flow and processing [3]. Recognising the aforementioned advantages, most AEC enterprises have started to use BIM in their projects and attempted not to perform traditional methods again, as BIM increases their productivity and greatly decreases the requests for information and rework [4], and even extend to the management of demolition waste [5]. Although the potential benefits of the technologies may seem evident, the industry adoption rate of BIM varies [6]. Kouide et al. found through an investigation on the Heathrow Airport Terminal 5 Project in London that although the latest software tools are available, major hidden technology constraints hinder their wide adoption in small and medium-sized enterprises (SMEs) [7]. Such constraints also exist in China, and we must admit that BIM adoption in SEMs in China is at an infant stage [8]. The Chinese central government has emerged as a major force for promoting BIM adoption [9]; the Ministry of Housing and Urban-Rural Development has mandated a guideline that aimed at a national BIM adoption rate of 90% by the year 2020 in large- and medium-sized buildings [10]. The main objectives of this guideline are to improve the digitisation of buildings. However, buildings are limited to large- and medium-sized buildings, which are mainly constructed by large enterprises. To some degree, BIM adoption in SMEs in China is largely overlooked. SMEs have greatly contributed to the economic development of existing regions or countries [11], and relying on large enterprises to improve the digitisation of buildings is insufficient. The problem that must be solved is how to achieve BIM adoption in SMEs in China.

Quantitative studies have investigated the influencing factors associated with BIM adoption for SMEs. Scholars, such as Gu, have confirmed that the factors affecting BIM adoption can mainly be grouped into technical tool functional requirements and needs and nontechnical strategic issues [6]. A case study conducted by Kouide et al. demonstrated that in terms of the time, cost, and effort required to implement the technology, the current investment means that BIM is unlikely to be used in small, simple projects where a traditional computer-aided design (CAD) remains sufficient [7]. Goodridge et al. pointed out that SMEs' innovation capability is extraordinarily low due to fragmentation, limited collaboration, and risk-averse attitude [12]. According to a research on the BIM adoption state of UK construction industry SMEs, the challenges faced by SMEs include the short of investments, the lack of BIM skills and capabilities, the slow return on investment, the security of the model, and the necessity to establish a mechanism for BIM implementation plan [13]. In fact, the reasons for BIM adoption in SMEs are not simply a single issue but a combination of several issues [14]. Previous studies have insufficiently considered the linkages that underlie the critical stakeholders and influencing factors. Therefore, critical factors that challenge BIM adoption in SMEs must be reidentified and must consider what strategies can be adopted from a stakeholder network perspective.

In consideration of the objectives of this study, two aspects are mainly discussed. Firstly, the critical factors that affect or impede BIM adoption in SMEs are investigated from the stakeholder perspective. Secondly, strategies for handling the challenges during the process of BIM adoption in SMEs are proposed. For these objectives, we propose the social network analysis (SNA) to evaluate the stakeholder-related factors in the adoption stage of BIM. This study contributes to local governments and SMEs in mitigating the existing challenges and promoting BIM adoption in SMEs through provided strategies. A new frontier for BIM adoption in SMEs is also opened via a network analysis, which integrates the critical factors with related stakeholders.

The remainder of this paper is organised as follows. Section 2 outlines the literature review of BIM adoption in SMEs. Section 3 demonstrates the research methodology, data collection and data processing. The results including node, link, and network levels are displayed in Section 4. Section 5 discusses the critical factors and corresponding strategies, and Section 6 summarises this paper.

2. Literature Review

2.1. The Development Process of BIM. The concept of BIM first appeared in 1992, published by the Automation in Construction journal in an article entitled "Modelling multiple views on buildings" [15]. Since then, studies on BIM have gradually emerged, and it has been defined in several ways. Paavola et al. described BIM from three aspects: (1) BIM is an object-based 3D model that can achieve visualisation and simulation of the building. (2) BIM can be perceived as a new way of working collaboratively through the entire life cycle of the building. (3) BIM can be considered a central way for promoting productivity and business results [14]. Succar et al. held the point that BIM can be perceived both as a technology and process [16]. In the early stages of BIM research, most articles regarded BIM as a technical means [17]. Gradually, Both et al. found that it is not enough to set the goal only on a technical level. The combination of technical and methodological aspects particularly contributes to the enhancement of understanding economic issues [18]. Gradually, a further comprehensive view on BIM emerged, which describes it as the process of generating, storing, managing, exchanging, and sharing building information in an interoperable and reusable way [19].

The project-based nature and fragmentation of the construction industry lead its productivity development to lag behind that of other industries [2, 20]; the emergence of BIM aims to solve this problem [21]. However, Porwal pointed out that potential conflicts and risks will exist due to the change in work practices by the adoption of BIM [22]. On the basis of Chang et al.'s benefit-cost theory of BIM, we divided the development stage of BIM into three levels. In level 1, only a small group of AEC firms use BIM in daily production activities because the extra cost arising from BIM is high. As the application broadens (considerable life cycle phases), deepens (BIM levels), and diversifies (the benefits of various analyses), industry players acquire additional potential benefits from BIM [23]. Figure 1 shows the benefit-cost curve of BIM (the red curve represents the benefits of using BIM and the black curve represents the cost of using BIM). Numerous studies have recently been published to support that BIM is beneficial, since it presents an accurate cost estimation, is time saving, exhibits few design coordination errors, and presents energy-efficient design solutions [24–26]. Wang et al. found that early adoption of facility management in design stage with BIM can obviously reduce life cycle costs [27]. Paavola and Miettinen proposed a novel concept of "virtual materiality"; that is, BIM models provide dynamic but tangible ways for collaboration [14]. However, Arayici et al. found that stakeholder collaboration expands organisational boundaries [28]. When using BIM models in the construction industry, more stakeholders than ever will be involved in the entire phases of a project. As a result, critical factors that profoundly affect BIM adoption must be determined from the stakeholder perspective.

2.2. Factors and Stakeholders Related to BIM Adoption in SMEs. With respect to BIM adoption in AEC industries, researchers have identified sufficient influencing factors. Johnson et al. partly conceived the lack of initiative and training, the fragmented nature of AEC industries, the varying market readiness across geographies, and the industry's reluctance to change existing work practices as the reasons why BIM is at a relatively low level in AEC industries [29]. In addition, scholars found that collaborative environment and management process [30], motivation and BIM capability [23], a clear division of roles and responsibilities, and benefits allocation [31] also play important roles in the adoption of BIM in SMEs. On the basis of an empirical study of the motivations for BIM adoption in China, Cao et al. stressed

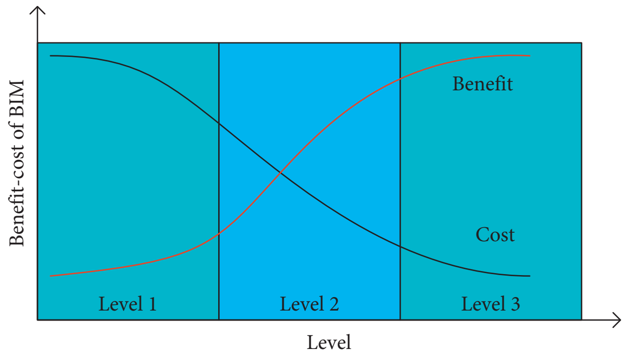


Figure 1: Benefit-cost curve of BIM.

that a robust understanding of how stakeholders implement a BIM adoption decision and which factor will affect it should be established [8]. As previously mentioned, these studies have helped us understand the factors that limit BIM adoption in AEC industries. However, Poirier described BIM as a technological innovation for construction organisations [32]. In terms of this respect, evidence suggested that SMEs treat innovation differently compared to large firms [33]. It is vital to find out the influencing factors to gain further insight into the BIM adoption for SMEs.

SMEs are usually defined by its characteristics including number of employees, enterprise turnover, asset size, and capital requirement [34]. The Ministry of Industry and Information Technology of the People's Republic of China (MOIIT) defined SMEs as companies that use approximately 10–300 employees [35]. With respect to BIM in SMEs, Jayasena first emphasized the terminology as these terms have yet to start their journey towards BIM transformation [36]. Rodgers et al. revealed that the level of understanding of BIM in Australia was much lower in SMEs, and there is prejudice to the requirements and challenges of implementing BIM in SMEs [37]. Based on Lam's study, he pointed out that guidance and frameworks in the UK to help SMEs to make an informed decision on BIM adoption are currently lacking [38]. Compared with developed countries, this situation also exists in China. China Construction Industry BIM Application Analysis report (2017) shows that only 10.4% of Chinese enterprises began to promote the deployment of BIM on a large scale [39]. Almost all of these enterprises are large enterprises, which means no SMEs. It widened the gap between SMEs and large firms in the market [40], despite the fact that research has confirmed the increase of using BIM by SMEs is a key condition for achieving the transformation of construction industry [38]. The above-mentioned influencing factors include diverse stakeholders, who are directly or indirectly involved in the process of BIM adoption in SMEs. The stakeholders mainly comprise the government, contractors, designers, software developers, owners, BIM consultants, and so forth.

Studies have also highlighted the factors that impeded BIM adoption in SMEs. Kouide et al. indicated that the BIM environment requires training, timing, and costing software, but SMEs would not pay additional fund where a normal traditional 2D method is adequate [7]. Resources limitation, competition, and functional structure were also influential barriers to BIM adoption in SMEs [38]. Grounded in a quantitative study performed on more than 200 manufacturing plants, Belvedere et al. found that SMEs cannot invest in the latest manufacturing practices and technologies that can improve their performance [41]. Meanwhile, Goodridge et al. revealed that fragmentation, limited collaboration, and risk-averse attitude are partly the reasons why SMEs are in low levels of innovation capability [12]. In fact, SMEs are naturally inclined to adopt reliable methods to ensure the return on investment (ROI) [32]. In the absence of sufficient evidence, the use of BIM is considered to be too risky due to the limited resources in SMEs [42]. Despite the lack of sufficient resources and key assets [38], Rosenbusch et al. deemed that SMEs are usually more flexible in their organisational structure and can quickly exploit new business opportunities in the market compared with large firms [43]. On the basis of an experiment with two SMEs, Hochscheid et al. brought to light that when actors are satisfied with the experiment results in their usual practices, they will take the initiative to invest in BIM and integrate more advanced BIM uses [44]. Project size was also investigated in Both and Petra's study, indicating that the use of BIM increases as the project grows in size [18], but they did not mention why the BIM adoption rate in SMEs is low. As discussed above, in this study, we considered the critical challenges that impede BIM adoption in SMEs from a stakeholder's perspective and proposed strategies to mitigate the challenges.

3. Research Methodology and Processes

3.1. Methodology

3.1.1. SNA. The concept of SNA was proposed by Moreno in 1934 [45]; since then, it has become an effective tool for researchers and practitioners who cover construction project management [46], information science [47], and risk management [48]. SNA is grounded on graph theory, sociology, and anthropology [49], which assumes that network members can interact with one another and their behaviours are largely influenced by the relationship pattern embodied in the network [50]. Accordingly, SNA is defined as a set of connections among stakeholders with additional attributes, which can be used to explain the social behaviours of the stakeholders involved [51]. Mok et al. applied SNA to solve the problems related to stakeholders in construction project management and other research fields and found that this is an effective means [52]. In order to identify critical factors for BIM adoption in SMEs, we applied SNA as it can link factors with associated stakeholders and quantify the interrelationships among different network nodes [48].

All nodes are encoded as SmFn in SNA, where m denotes the stakeholders and n represents the associated factors. For instance, S2F5 indicates the second stakeholder associated with the fifth influencing factor. Each node has a unique colour that represents corresponding stakeholder groups and factor categories. An arrow from node SxFy to node SwFz in the network indicates the relationship between SxFy and SwFz, and the thickness represents the influence degree of the relationship. Nodes with multiple links will be located at the centre of the network, while nodes with fewer connections will be on the edge of the graph. Density, node degree, status centrality, brokerage, and betweenness centrality are also the indicators for analysing the nodes and network [50]. These indicators provide a holistic understanding on the factor network.

3.1.2. Research Framework. Shi et al. adopted the SNA method to determine the critical factors to achieve dockless bike-sharing sustainability, which followed a classical framework, including factor identification, factor evaluation, key factor analysis and stakeholder analysis, and challenges mitigation [53]. Previous studies have shown that combining traditional frameworks with SNA can effectively manage stakeholder-related factors [46, 54]. Inspired by the above-named scholars, we (1) identified the factors that and the corresponding stakeholders who affect BIM adoption in SMEs, (2) estimated the relationships among factors, (3) analysed critical factors and stakeholders, and (4) conducted responding strategies. Figure 2 shows the main framework processes.

3.2. Processes

3.2.1. Data Collection. Interviews were conducted to collect data, which provided considerable information and a face-to-face interaction between investigators and interviewees. According to Brinkmann, open discussion and information sharing with different participants can mitigate ambiguities whilst improving data reliability [55]. In Section 2.2, government (S1), contractors (S2), designers (S3), software developers (S4), owners (S5), and BIM consultants (S6) were recognised as key stakeholder groups in BIM adoption in SMEs. We interviewed all six stakeholder groups to avoid a biased judgement and ensure data representativeness. S1 interviewees must come from a building department and involve in the management of BIM adoption. All interviewees from S2, S3, and S5 worked in SMEs (the number of employees is between 10 and 300) and have more than six years working experience. S2, S3, and S5 interviewees must also be knowledgeable about BIM or experienced related projects. S4 interviewees mainly came from Glodon (a native Chinese software developer, which has 10 years of BIM experience) and PMSbim (a local BIM developer in China, which is established in 2011). To find the appropriate people, interviewees from S6 were primarily introduced by S5 due to their close relationship. We do not pay particular attention to the natures of S5 and S6, because this paper discusses the BIM adoption by SMEs. However, S5 and S6 are mainly service providers. Initially, we contacted several familiar interviewees from corresponding stakeholder groups, and then a snowball sampling was used to encourage additional potential respondents to participate in our survey. We contacted 76 stakeholders via telephone, email, or face-to-face talk; 26 of them did not have sufficient knowledge or were not interested in our study topic, and 19 claimed that they were ineligible for the investigation. Thus, 31 participants were identified as eligible interviewees (with the exception of seven members in group S2, the number of members in the other groups was six). The sample met the requirements of previous studies [48, 53, 54].

Prior to the formal interview, we email all interviewees with background information and content to help them prepare for follow-up questions. On the basis of the questions proposed by Li et al. [48], we asked the interviewees to answer the following: (1) what factors do you think may affect BIM adoption in SMEs? (2) provide other factors that are not included in the above list (a reference list of stakeholder factors compiled by literature review), and (3) how are these identified factors relevant to the corresponding stakeholders? On the basis of their reply and combined with our literature review, we recompiled our influencing factors and the corresponding stakeholder list, delivered the manuscripts to respondents for feedback, and finally formed our list, as shown in Table 1.

Face-to-face interviews with semistructured attributes were conducted to find out the potential interconnections among the influencing factors. A detailed verbal explanation was provided to each interviewee when they were confused on the questions to minimise ambiguities. In SNA, nodes refer to the factors identified before, and links are defined as the influence of a stakeholder-related factor over another factor. Interviewees were asked to determine the direction of the potential effect clearly, as the interaction may be mutual. In other words, if a link exists between SxFy and SwFz, then SxFy can affect SwFz, and the corresponding stakeholder groups Sx and Sw will be asked to assess the linkage between SxFy and SwFz. Three types of questions were asked: (a) Can factor SxFy affect SwFz when using BIM method in a project (the link direction)? (b) What is the likelihood of this potential link? (c) If SxFy affects SwFz, then to what degree is the influence? On the basis of similar studies conducted by former scholar, we followed a five-level Likert scale, where "1" and "5" denote the lowest and highest levels, respectively [48, 53]. The overall effect of a link (P) can be represented by multiplying the likelihood of this link with the degree of influence.

3.2.2. Data Processing. In some cases, the associated stakeholders cannot agree on the final outcome of a linkage evaluation ($0 \leq P \leq 25$). Different stakeholders typically have different criteria for certain links. When this phenomenon happens, we calculate the degree of variation ($V = (P_{\max} - P_{\min})/25$, where $P_{\max}$ = the maximal effect of the link and $P_{\min}$ = the minimal effect of the link). If $V \leq 0.2$, which indicates that the result is acceptable, then the weight of the link will be reflected by the median of the evaluation [66]. If $V > 0.2$, which means that the result is unacceptable, then a re-evaluation with related stakeholders must be performed until an acceptable result is generated. Given this situation, we organised an online meeting via WeChat (a social software in China) and obtained the ultimate data. We imported the collected data into NetMiner 4 for factor network visualisation and analysis. Critical factors, links and corresponding stakeholders were identified further.

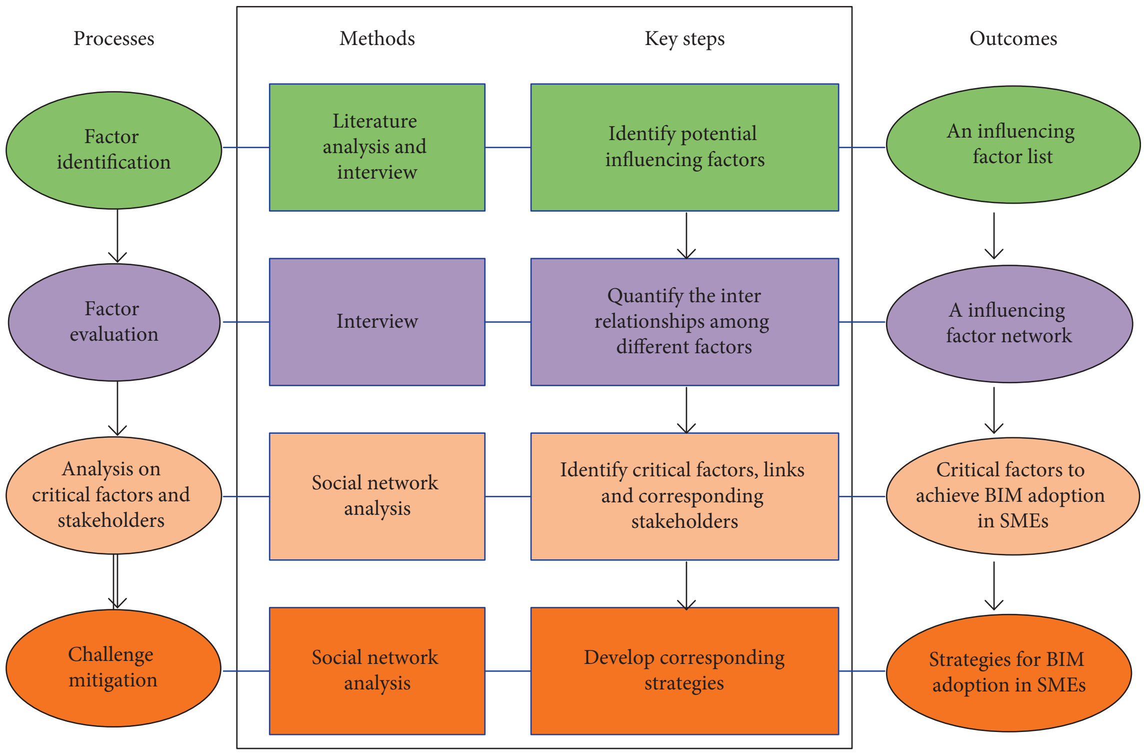


Figure 2: Research framework.

4. Results

On the basis of the literature analysis and semistructured interviews, 33 factors and 54 network nodes were identified, as shown in Table 1. On the basis of the different characteristics of these factors, we classified the 33 factors into 8 categories, namely, data (C1), cost (C2), technology (C3), perception (C4), contract (C5), collaboration (C6), legal (C7), and organisation (C8).

4.1. Network-Level Results. The factor network consists of 54 influencing factor nodes connected by 336 links, as shown in Figure 2. An arrow from nodes SxFy to SwFz indicates that SxFy can affect SwFz. The thickness of this arrow represents the influence level. Influencing factors with numerous links are at the centre of the network, while the less connected nodes are close to the graph boundary, as shown in Figure 3. A large number of interconnected relationships mean that the promotion of BIM adoption in SMEs is complex. The network density is 0.113, which indicates that the network is intensive and each factor has a close relation. S1 (governments), S3 (contractors), and S5 (owners) are at the network centre, which implies that governments, contractors, and owners are dominant in BIM adoption in SMEs.

4.2. Node and Link-Level Results. We explored the direct and indirect propagation effects of individual nodes to identify the key factors that influence BIM adoption in SMEs. Figure 4 shows the status centrality map, including all factors. Factors at the map centre play important roles in the network. Nodes S1 (governments), S3 (contractors), and S5 (owners) assume the central position, thereby implying the important role they play in BIM adoption in SMEs.

Out degree, degree difference, and ego size were used on the basis of previous studies to measure the roles of nodes in the network [48, 67]. The out degree reflects the range of direct influence, whereas a high degree of factor directly affects several neighbours in the network. The degree difference is equal to the gap between the out and in degrees [68]. A stakeholder issue with a large degree difference can be interpreted as exerting more influence on their neighbours than on acceptance [48]. If a factor has a large ego network size, numerous factors will be closely related to this factor [54]. In terms of the three indicators, we list the top 10 nodes in Table 2. A node with a high value often plays an important role in the network.

Brokerage is considered a valuable network index that demonstrates the different functions and capabilities of factor nodes in connection subgroups. These nodes play an important role in connecting various stakeholder groups; they are also crucial to BIM adoption in SMEs. We selected the top 10 nodes in the brokerage analysis, and they are shown in Table 3.

On the basis of betweenness centrality analysis, Table 4 displayed top 10 factors and links to show the capability of a factor or link to control the influence on other factors. Removing these factor nodes or links can considerably promote BIM adoption rates in SMEs.

5. Discussion

5.1. Critical Factors and Challenges Identified. On the basis of a previous study, the critical factors and links we selected will

Table 1: Influencing factors and relevant stakeholders.

Factor ID	Stakeholder node	Factor node	Factor name	Source	Category
S2F1 S5F1	S2 S5	F1	Security of confidential data	[56]	C1
S2F2 S3F2 S4F2 S5F2 S6F2	S2 S3 S4 S5 S6	F2	Inserting, extracting, updating, or modifying the data in the BIM model	[57]	C1
S2F3 S3F3 S4F3	S2 S3 S4	F3	Accuracy of data transmission	Interview	C1
S2F4	S2	F4	Limited budget	[42, 44, 58]	C2
S2F5 S3F5 S5F5	S2 S3 S5	F5	High costs to educate people	[42, 59]	C2
S2F6 S5F6	S2 S5	F6	High-economic investment in the facilities	[40, 60]	C2
S1F7 S5F7	S1 S5	F7	Inadequate funding	[38]	C2
S5F8	S5	F8	Downstream beneficiaries do not pay compensation to upstream for additional cost and effort	Interview	C2
S4F9	S4	F9	Standards and protocols with a common language	[42]	C3
S5F10	S5	F10	Difficulties in measuring the effects of BIM	[42, 61]	C3
S4F11	S4	F11	Interoperability among different software	Interview	C3
S5F12	S5	F12	Unlikely to find BIM that matches SMEs' specific practice	[42, 61]	C3
S4F13	S4	F13	Lack of subcontractors who can use BIM technology	[42]	C3
S2F14 S3F14 S5F14	S2 S3 S5	F14	Lack of case studies and samples	[42]	C3
S4F15	S4	F15	Scalability to handle small simple and large complex projects	[38, 62]	C3
S2F16 S3F16	S2 S3	F16	Reluctance to change	[13]	C4
S2F17 S5F17	S2 S5	F17	New roles and responsibilities	[22]	C5
S5F18	S5	F18	Awareness about BIM	Interview	C4
S5F19	S5	F19	Client interest or request for BIM	[42]	C4
S2F20	S2	F20	Habits of 2D-based work	[18]	C3
S5F21	S5	F21	New contractual relationships	[63]	C5
S2F22 S5F22	S2 S5	F22	New project delivery methods	[7]	C5
S2F23 S3F23 S5F23	S2 S3 S5	F23	Contractual responsibilities for inaccuracies in the BIM model are unclear	[57]	C5
S2F24	S2	F24	Distribution of benefits	[21]	C5
S5F25	S5	F25	Lack of BIM-ready samples for contractual documents	[18]	C5
S3F26	S3	F26	Several people are concerned in the planning and design phases	[13]	C6
S3F27	S3	F27	Interoperability among different project teams	[6]	C6
S2F28 S5F28	S2 S5	F28	Substantial adjustment to the current process/practice change	Interview	C6
S3F29 S5F29	S3 S5	F29	Ownership and intellectual property rights over BIM models	[2, 6]	C7
S2F30	S2	F30	New responsibilities among projects participants	[64]	C7
S1F31	S1	F31	No specific law to address BIM-related disputes	Interview	C7
S5F32	S5	F32	Organisational restructure to support BIM	[42, 60]	C8
S2F33 S5F33	S2 S5	F33	Changing well-established non-BIM procedures	[42, 65]	C8

vary slightly in accordance with different ranking criteria; we followed a principle that selects the top factors from each ranking list in Section 4 as critical factors, often selecting three to five factors [48]. These factors play an important role in the network. Removing these nodes and links reduces the overall complexity of the factor network [46, 67]. Factors that appear many times in different ranking lists are identified as critical because they have multiple functions that support factor networks [53, 54]. Following these principles, 10 influencing factors and 10 links were identified as critical for BIM

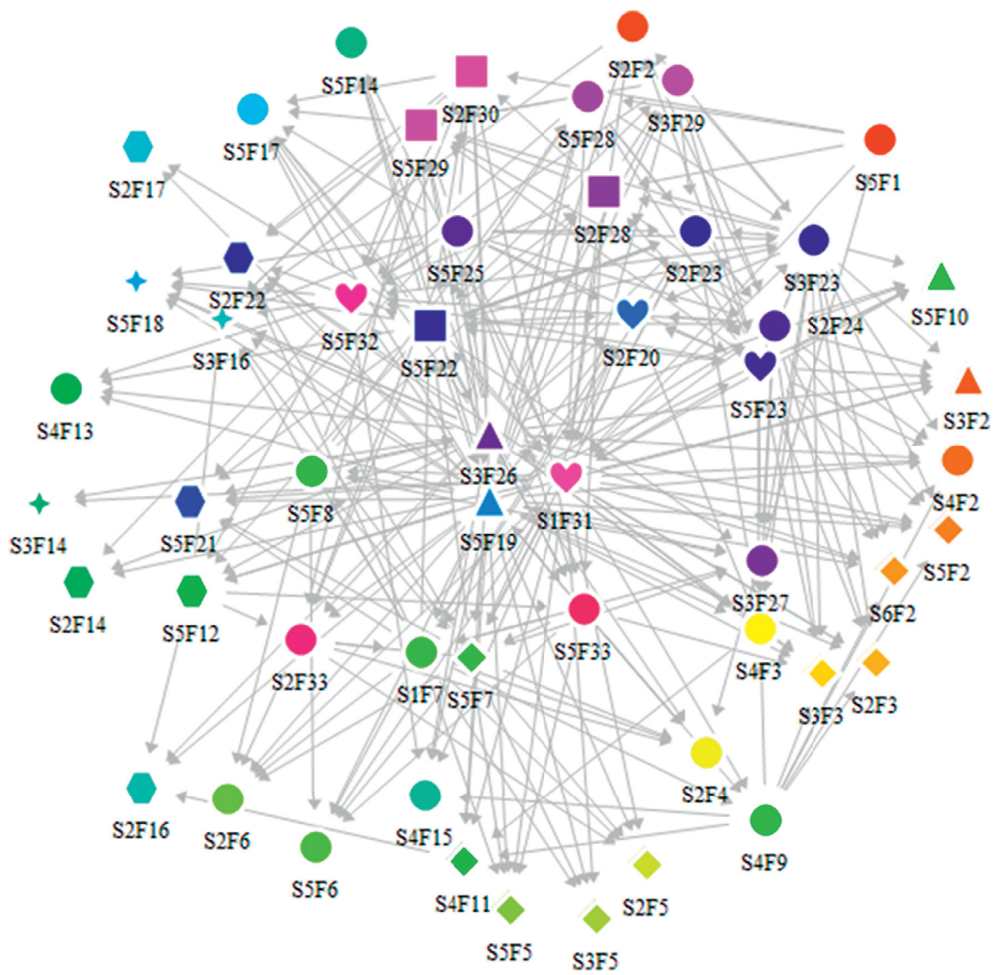


Figure 3: Stakeholder-related influencing factor network.

adoption in SMEs, as shown in Table 5. We divided them into six categories and explained them briefly to show the basic principles of this classification for understanding the meaning of key factors and links. The basic rationale of this classification is that if one of the 10 key factor nodes and the selected 10 key links exist in multiple links at the same time, which may lead to multiple problems, then that is a key challenge.

5.2. Strategies to Challenges Mitigation. From these analyses, we proposed five strategies to mitigate challenges in BIM adoption in SMEs. These strategies, including cultivating the BIM perception of SMEs, integrated project delivery (IPD), strengthening the legal environment for BIM adoption in SMEs, and developing native software and standards and cloud-based technology. These strategies are mainly based on the view of governments, software developers, owners, and contractors who are the main stakeholders in the adoption of BIM by SMEs. Following these management strategies, we constructed a governance framework, as shown in Figure 5.

5.2.1. Strategy 1: Cultivating the BIM Perception of SMEs. Incentives are major drivers of new technologies, whilst great efficiency is not enough to change business behaviour. Governments must play a positive role at the early stages of BIM adoption in SMEs. Issues, such as high education cost and high-economic investment in the facilities, must be solved through mandatory legislation and supervision. Clear compensation institutions must be provided to mitigate apprehensions, for instance, implementation and maintenance costs outweigh its usefulness. Apart from costs, the interest and willingness of project managers and engineers to use BIM also play important roles [73]. Following this principle, governments should strengthen BIM training. For example, they can force SMEs to set up a BIM department (with only 1–2 people required) and can train the BIM staff responsible for training within the enterprises and reporting on the result of the training. In this way, they are changing SMEs' attitude towards new technologies, formulating positive perceptions, and promoting BIM adoption in SMEs. As such, challenges 1 (SMEs are short on resources) and 3 (lack of BIM awareness) can be addressed.

5.2.2. Strategy 2: IPD. We introduced an IPD concept to address challenge 2 (collaboration challenges) identified in Table 5. The combination of BIM and IPD has been

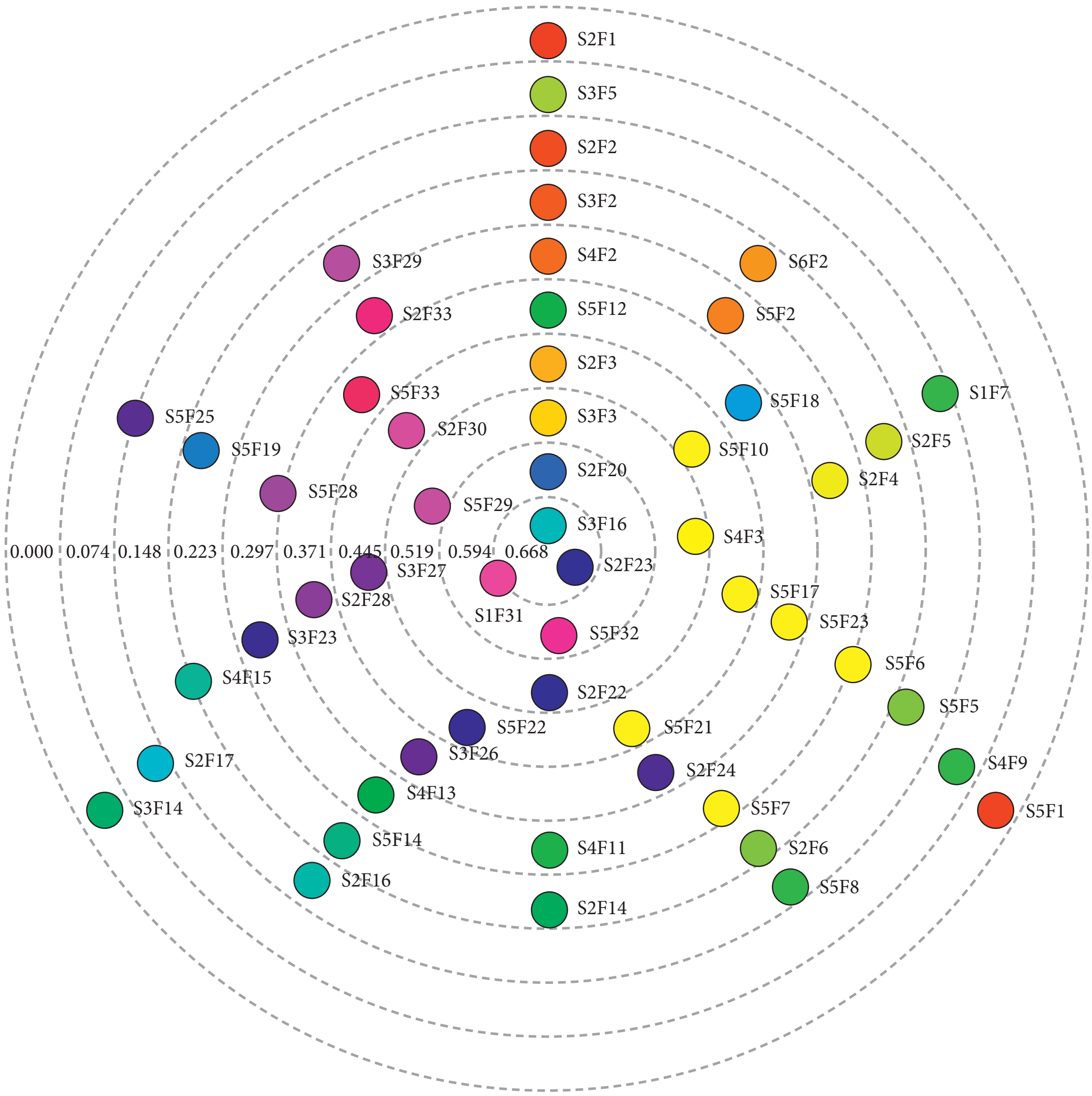


Figure 4: Status centrality map.

Table 2: Critical factors based on degree analysis, ego network, and status centrality.

Ranking	Factor ID	Ego size	Factor ID	Out status centrality	Factor ID	Out degree	Factor ID	Degree difference
1	S5F19	46	S5F19	3.15	S5F19	46	S5F19	39
2	S1F31	41	S5F22	1.696	S1F31	36	S3F26	28
3	S3F26	35	S1F31	1.675	F3F26	33	S1F31	24
4	S5F22	28	S3F26	1.627	S5F22	26	S5F22	15
5	S2F24	23	S3F23	1.247	S2F24	19	S5F25	14
6	S5F23	22	S2F24	1.132	S5F23	19	S1F7	14
7	S3F23	22	S5F23	0.973	S1F7	19	S2F24	11
8	S1F7	20	S1F7	0.968	S3F23	18	S5F23	11
9	S5F7	19	S5F25	0.762	S5F25	17	S3F23	11
10	S5F32	18	S5F7	0.643	S5F7	16	S5F7	10

widely supported in the literature as a method for solving the problem of limited collaboration in the construction industry [74, 75]. IPD is defined as the simultaneous development of a product and service during the planning stage. Using IPD increases the number of participants involved in the design, which leads to a good understanding among mean parties at the early stage. Therefore, a further detailed upstream analysis can be conducted on the product model, so that the product design process can be easily understood and the structure

Table 3: Critical factors for BIM adoption in SMEs based on brokerage analysis.

Ranking	Factor ID	Coordinator	Gatekeeper	Representative	Itinerant	Liaison	Total
1	S1F31	0	0	0	10	284	294
2	S5F19	0	7	0	13	163	183
3	S5F22	2	14	14	18	107	155
4	S3F26	0	3	0	7	81	91
5	S3F23	0	1	9	7	46	63
6	S5F23	0	1	11	7	44	63
7	S5F32	0	0	10	0	50	60
8	S2F24	0	1	11	6	33	51
9	S5F7	0	2	12	2	26	42
10	S5F33	0	0	6	0	28	34

Table 4: Critical factors and links for BIM adoption in SMEs based on betweenness centrality.

Ranking	Factor ID	Node betweenness centrality	Link ID	Link betweenness centrality
1	S1F31	0.1044	S2F33⟶S1F7	63.9
2	S5F19	0.0602	S4F11⟶S3F26	58.6
3	S5F22	0.0446	S5F33⟶S5F7	57.7
4	S1F7	0.0441	S2F33⟶S5F7	56.7
5	S5F7	0.0421	S5F32⟶S5F12	54.5
6	S5F33	0.0367	S5F12⟶S5F33	48.3
7	S3F26	0.0345	S5F12⟶S2F33	47.5
8	S2F33	0.0327	S5F7⟶S5F19	47.2
9	S5F1	0.0193	S2F30⟶S5F33	45.1
10	S5F12	0.0189	S5F29⟶S2F33	43.8

Table 5: Critical factors and challenges for BIM adoption in SMEs.

Critical factors and links	Associated critical stakeholder	Primary challenges and explanation
S1F7 S1F7⟶S2F4 S1F7⟶S5F5	Governments Governments Governments	1. SMEs are short on resources: SMEs are often extremely short on project resources [69]; as a result, they cannot afford extra overheads on infrastructure construction and training people to support new technology. SMEs' downstream beneficiaries also do not pay compensation to upstream for additional cost and effort. Thus, companies with limited human, time, and financial resources must focus on what they consider to be important criteria for success.
S3F26 S5F22 S2F30⟶S5F33 S5F22⟶S3F26	Designers Owners Contractors Owners	2. Collaboration challenges: The fragmented nature of construction industries leads to difficulties in sharing information and collaboration among different participants. Meanwhile, willingness to share information among project participants is considered the most critical [70]. The lack of cooperation consciousness and 2D-based work habits cause the production efficiency of the construction industry to be considerably lower than that of other industries, which is unconducive to the sustainable development of SMEs.
S5F19 S5F7⟶S5F19 S5F19⟶S3F16	Owners Contractors Owners	3. Lack of BIM awareness: As a new technology, BIM has been adopted and applied by large enterprises and has been gradually combined with project management and even enterprise management. However, SMEs lack the awareness of BIM and neither understand what BIM is nor how BIM is combined with the current working methods. Thus, the benefits of BIM to enterprises are difficult to determine.
S1F31 S2F24 S3F23 S1F31⟶S3F23 S5F29⟶S2F33	Governments Contractors Contractors Governments Owners	4. Legal disputes and uncertainties in policies: The construction industry is a complex process involving numerous people and information. When design information is generated in collaboration among several participants, identifying inaccurate responsibilities can be problematic [65]. No law explicitly addresses BIM disputes, and SMEs are worried about their own interests.

Table 5: Continued.

Critical factors and links	Associated critical stakeholder	Primary challenges and explanation
S5F12 S5F10 S4F11⟶S3F26	Owners Owners Software developers	5. Difficulties in meeting SMEs' needs: A 3D coordination and design review is considered the most effective and prevalent application of BIM today [71]. Projects in SMEs may be too simple to determine the benefits of BIM. Scalability to handle small, simple, and large, complex projects must be improved in an environment where conventional CAD remains adequate.
S5F1 S4F3⟶S4F11	Owners Designers	6. Concerns about data and information: The BIM model must store considerable data, involving input, output, and update. The accuracy of data transmission among different project teams must be ensured. Enterprises will not upload important data if data security cannot be guaranteed. Data security must be ensured through encryption or the use of secure file exchange servers during transmission [72].

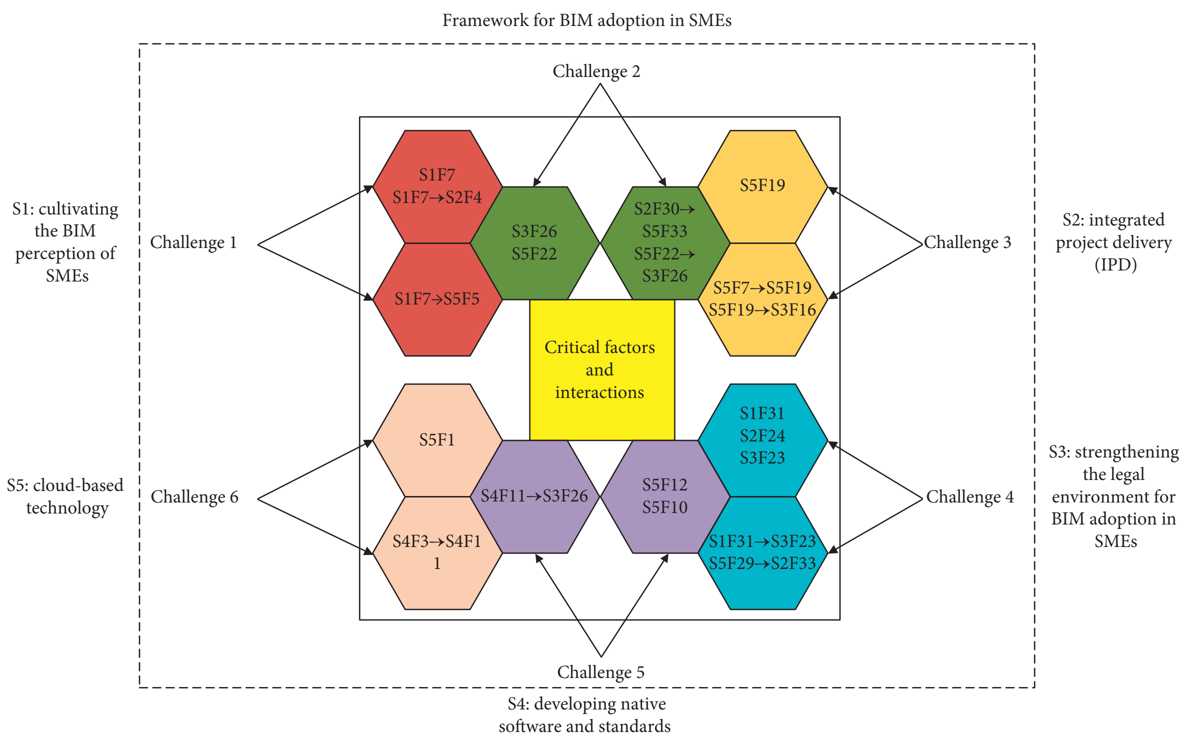


Figure 5: Framework for BIM adoption in SMEs.

can be adjusted in detail [76]. Besides, IPD also stimulates people to be involved in a project for the benefit of the entire project. BIM is more than a technical means with a social dimension, but it has no contractual authority to manage stakeholders. As a result, a formal infrastructure and a BIM manager are required to manage stakeholders across organisations.

5.2.3. Strategy 3: Strengthening the Legal Environment for BIM Adoption in SMEs. Resolving legal and contractual disputes is essential to SMEs. SMEs are more focused on immediate interests than large enterprises. When a potential risk exists, SMEs will select traditional project delivery over BIM to ensure the interests of the enterprises. BIM programmes are full of collaboration, in which individuals coordinate their work by using objects created or designed by others. Nevertheless, conventional legal instruments implemented to BIM project seldom accommodate the collaborative nature that is generated by BIM. When the design information is engaged in collaboration among numerous participants, identifying inaccurate responsibilities is vital. For instance, legislation can define the specific information that different actors are responsible for communicating. When the risk is equally shared through legislation, the return must be shared. Accordingly, part of the owner's savings must be shared with participating project members due to increased productivity. This aspect should be specified in the contract to facilitate BIM adoption by SMEs. As such, Challenge 4 (legal disputes and uncertainties in policies) can be governed.

5.2.4. Strategy 4: Developing Native Software and Standards. Software is a means for realising BIM application, but best results are only achieved when cross-disciplinary standards and platforms can be interoperable. The success of BIM adoption depends more on how a company combines BIM technology with their workflow than on how well prepared it is, thereby allowing teams to adapt to the technologies to suit their existing work practices [77]. From this point of view, without changing the existing building development approval process, a set of building code-related standards and software must be developed to assist SMEs to build the model correctly. If BIM-related software can automatically generate 2D drawings and related documents for building approval process, it will improve the adoption of BIM by SMEs. Establishing a BIM-based case library to fulfil local needs is also crucial. Well-documented experiences contribute to assessing achievements, problems, and challenges, thereby facilitating BIM adoption in SMEs. These strategies could play an important role in the mitigation of Challenge 5 (difficulties in meeting SMEs' needs).

5.2.5. Strategy 5: Cloud-Based Technology. Projects in construction industries often have a long life cycle, which involves quantitative data. Inserting, extracting, updating, and modifying data and ensuring the accuracy of data transmission in BIM model are important problems. Drawing on experience in other industries, software developers in BIM have moved towards cloud services to manage data. On the basis of the powerful computing and data-processing capability, embedding cloud technology in BIM can solve these problems. Interoperability issues can also be addressed as a cloud-based BIM solution will allow multiple BIM practitioners to work on the same version of BIM data [58]. Restricting password protection and assessing authority regulations can assure security and privacy that address users' concerns about security. Furthermore, cloud-based BIM enables users who have an Internet connection to synchronise their data on more than one device, such as personal computer and smart phone. In this way, infrastructure cost can be saved and bring convenience to SMEs. As a result, Challenge 6 (concerns about information and data) can be solved through this approach.

6. Conclusion

BIM adoption in SMEs is complicated, in which numerous stakeholders and various influencing factors are involved. In this paper, we list the factors that influence BIM adoption in SMEs on the basis of previous studies and interviews. We used SNA to investigate the underlying network of stakeholder-associated influencing factors and links and divided them into six challenges: (1) SMEs are short on resources, (2) collaboration challenges, (3) lack of BIM awareness, (4) legal disputes and uncertainties in policies, (5) difficulties in meeting SMEs' needs, and (6) concerns about data and information. We proposed five corresponding strategies, namely, cultivating the BIM perception of SMEs, IPD, strengthening the legal environment for BIM adoption, developing native software and standards, and cloud-based technology, to mitigate the challenges considering that removing these factors and links will greatly reduce network complexity.

The strategies provide a strong reference for building departments in China and software developers to apply appropriate approaches for increasing BIM adoption in SMEs. For example, related government departments can conduct training activities to improve BIM awareness in SMEs and mandate specific policies to address BIM disputes. For software developers, they can develop a local software to best suit China's current approval process.

The main limitations of this study are two. Firstly, a small-sample survey, which only covered 31 people, was used in this study due to the difficulty of researchers to find sufficient interviewees. The sample size may influence our results. Secondly, not all stakeholder groups involved in BIM adoption in SMEs were included in our study. Subcontractors, material suppliers, and mechanical, electrical, and plumbing workers are also stakeholder groups related to BIM adoption in SMEs. Therefore, a wider group of stakeholders should be invited to carry out follow-up studies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

There are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors thank the anonymous referees for their constructive suggestions.

References

[1] D. Cao, G. Wang, H. Li, M. Skitmore, T. Huang, and W. Zhang, "Practices and effectiveness of building information modelling in construction projects in China," *Automation in Construction*, vol. 49, pp. 113–122, 2015.

[2] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, Wiley Publishing, Hoboken, NJ, USA, 2008.

[3] B.-j. He, M. Ye, L. Yang, X.-P. Fu, B. Mou, and C. Griffy-Brown, "The combination of digital technology and architectural design to develop a process for enhancing energy-saving: the case of Maanshan China," *Technology in Society*, vol. 39, pp. 77–87, 2014.

[4] S. L. Fan, M. J. Skibniewski, and T. W. Hung, "Effects of building information modeling during construction," *Journal of Applied Science and Engineering*, vol. 17, no. 2, pp. 157–166, 2014.

[5] J. Chen, Y. Su, H. Si, and J. Chen, "Managerial areas of construction and demolition waste: a scientometric review," *International Journal of Environmental Research and Public Health*, vol. 15, no. 11, p. 2350, 2018.

[6] N. Gu and K. London, "Understanding and facilitating BIM adoption in the AEC industry," *Automation in Construction*, vol. 19, no. 8, pp. 988–999, 2010.

[7] T. Kouide and G. Paterson, "BIM as a viable collaborative working tool: a case study," in *Proceedings of CAADRIA 2007*, Nanjing, China, April 2007.

[8] D. Cao, H. Li, G. Wang, and T. Huang, "Identifying and contextualising the motivations for BIM implementation in construction projects: an empirical study in China," *International Journal of Project Management*, vol. 35, no. 4, pp. 658–669, 2017.

[9] J. Zhang, Y. Long, S. Lv, and Y. Xiang, "BIM-enabled modular and industrialized construction in China," *Procedia Engineering*, vol. 145, pp. 1456–1461, 2016.

[10] MOHURD, *Guideline on the Application of Building Information Modelling*, MOHURD, Beijing, China, 2015, http://www.mohurd.gov.cn/wjfb/201507/t20150701_222741.html.

[11] A. Gunasekaran, B. K. Rai, and M. Griffin, "Resilience and competitiveness of small and medium size enterprises: an empirical research," *International Journal of Production Research*, vol. 49, no. 18, pp. 5489–5509, 2011.

[12] P. Goodridge, J. Haskel, and G. Wallis, *UK Innovation Index: Productivity and Growth in UK Industries*, Imperial College, London, UK, 2012.

[13] A. Ghaffarianhoseini, D. T. Doan, T. Zhang et al., "A BIM readiness and implementation strategy for SME construction companies in the UK," in *Proceedings of the 33rd CIB W78 Conference*, Brisbane, Australia, October-November 2016.

[14] S. Paavola and R. Miettinen, "Dynamics of design collaboration: BIM models as intermediary digital objects," *Computer Supported Cooperative Work*, vol. 27, no. 3–6, pp. 1113–1135, 2018.

[15] G. A. V. Nederveen and F. P. Tolman, "Modelling multiple views on buildings," *Automation in Construction*, vol. 1, no. 3, pp. 215–224, 1992.

[16] B. Succar and M. Kassem, "Macro-BIM adoption: conceptual structures," *Automation in Construction*, vol. 57, pp. 64–79, 2015.

[17] R. Santos, A. A. Costa, and A. Grilo, "Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015," *Automation in Construction*, vol. 80, pp. 118–136, 2017.

[18] P. v. Both, "Potentials and barriers for implementing BIM in the German AEC market: results of a current market analysis," in *Proceedings of the 30th eCAADe Conference on Digital Physicality*, pp. 151–158, Czech Technical University in Prague, Czech Republic, September 2012.

[19] R. Vanlande, C. Nicolle, and C. Cruz, "IFC and building lifecycle management," *Automation in Construction*, vol. 18, no. 1, pp. 70–78, 2009.

[20] D. Bishop, A. Felstead, A. Fuller, N., L. Jewson, and K. Kakavelakis, "Constructing learning: adversarial and collaborative working in the British construction industry," *Journal of Education and Work*, vol. 22, no. 4, pp. 243–260, 2009.

[21] M. Bresnen and C. Harty, "Editorial: objects, knowledge sharing and knowledge transformation in projects," *Construction Management and Economics*, vol. 28, no. 6, pp. 549–555, 2010.

[22] A. Porwal and K. N. Hewage, "Building Information Modeling (BIM) partnering framework for public construction projects," *Automation in Construction*, vol. 31, no. 5, pp. 204–214, 2013.

[23] C. Y. Chang, W. J. Pan, and R. Howard, "Impact of building information modeling implementation on the acceptance of integrated delivery systems: structural equation modeling analysis," *Journal of Construction Engineering and Management*, vol. 143, no. 8, 2017.

[24] D. Bryde, M. Broquetas, and J. M. Volm, "The project benefits of building information modelling (BIM)," *International Journal of Project Management*, vol. 31, no. 7, pp. 971–980, 2013.

[25] S.-L. Fan, "Intellectual property rights in building information modeling application in Taiwan," *Journal of Construction Engineering and Management*, vol. 140, no. 3, article 04013058, 2014.

[26] B. K. Giel and R. R. A. Issa, "Return on investment analysis of using building information modeling in construction," *Journal of Computing in Civil Engineering*, vol. 27, no. 5, pp. 511–521, 2013.

[27] Y. Wang, X. Wang, J. Wang, P. Yung, and G. Jun, "Engagement of facilities management in design stage through BIM: framework and a case study," *Advances in Civil Engineering*, vol. 2013, Article ID 189105, 8 pages, 2013.

[28] Y. Arayici, P. Coates, L. Koskela, M., C. Kagioglou, and K. O'Reilly, "Technology adoption in the BIM implementation for lean architectural practice," *Automation in Construction*, vol. 20, no. 2, pp. 189–195, 2011.

[29] R. E. Johnson and E. S. Laepple, *Digital Innovation and Organizational Change in Design Practice*, CRS Center, Texas A&M University, College Station, TX, USA, 2003.

[30] R. Eadie, M. Browne, H. Odeyinka, C. McKeown, and S. McNiff, "BIM implementation throughout the UK construction project lifecycle: an analysis," *Automation in Construction*, vol. 36, no. 1, pp. 145–151, 2013.

[31] D. Holzer, "Are you talking to me? Why BIM alone is not the answer," in *Proceedings of Association of Architecture Schools in Australasia*, Broken Hill, Australia, September 2007.

[32] E. Poirier, S. Staub-French, and D. Forgues, "Embedded contexts of innovation," *Construction Innovation*, vol. 15, no. 1, pp. 42–65, 2015.

[33] M. Sexton and P. Barrett, "A literature synthesis of innovation in small construction firms: insights, ambiguities and questions," *Construction Management and Economics*, vol. 21, no. 6, pp. 613–622, 2010.

[34] J.-L. Hsu and M.-C. Cheng, "What prompts small and medium enterprises to engage in corporate social responsibility? A study from Taiwan," *Corporate Social Responsibility and Environmental Management*, vol. 19, no. 5, pp. 288–305, 2011.

[35] MOIIT, "Circular on the issuance of standard provisions for the designation of small and medium-sized enterprises," 2018, http://www.miit.gov.cn/n1146285/n1146352/n3054355/n3057278/n3057286/c3592332/content.html.

[36] H. S. Jayasena and C. Weddikkara, "Assessing the BIM maturity in a BIM infant industry," in *Proceedings of the Second World Construction Symposium 2013: Socio-Economic Sustainability in Construction*, pp. 14-15, Colombo, Sri Lanka, June 2013.

[37] C. Rodgers, M. R. Hosseini, N. Chileshe, and R. Rameezdeen, "Building Information Modelling (BIM) within the Australian Construction Related Small and Medium Sized Enterprises: Awareness, Practices and Drivers," in *Proceedings 31st Annual ARCOM Conference*, pp. 691–700, UK Association of Researchers in Construction Management, UK, September 2015.

[38] T. T. Lam, L. Mahdjoubi, and J. Mason, "A framework to assist in the analysis of risks and rewards of adopting BIM for SMEs

in the UK," *Journal of Civil Engineering and Management*, vol. 23, no. 6, pp. 740–752, 2017.

[39] Glodon, "China construction industry BIM application analysis report," 2017, https://wenku.baidu.com/view/e1d07b4b53d380eb6294dd88d0d233d4b04e3f42.html.

[40] M. Reza Hosseini, E. A. Pärn, D. J. Edwards, E. Papadonikolaki, and M. Oraee, "Roadmap to mature BIM use in Australian SMEs: competitive dynamics perspective," *Journal of Management in Engineering*, vol. 34, no. 5, article 05018008, 2018.

[41] V. Belvedere, A. Grando, and T. Papadimitriou, "The responsiveness of Italian small-to-medium sized plants: dimensions and determinants," *International Journal of Production Research*, vol. 48, no. 21, pp. 6481–6498, 2009.

[42] M. R. Hosseini, S. Banihashemi, N. Chileshe et al., "BIM adoption within Australian Small and Medium-sized Enterprises (SMEs): an innovation diffusion model," *Construction Economics and Building*, vol. 16, no. 3, pp. 71–86, 2016.

[43] N. Rosenbusch, J. Brinckmann, and A. Bausch, "Is innovation always beneficial? A meta-analysis of the relationship between innovation and performance in SMEs," *Journal of business Venturing*, vol. 26, no. 4, pp. 441–457, 2011.

[44] E. Hochscheid, M. Ribereau-Gayon, G. Halin, and D. Hanser, "BIM implementation in SMEs: an experience of cooperation between an architect agency and a carpentry firm," in *International Conference on Computing in Civil and Building Engineering*, pp. 6–8, Osaka, Japan, July 2016.

[45] J. L. Moreno, "The sociometry reader," *Revue Française De Sociologie*, vol. 2, no. 4, p. 331, 1961.

[46] X. Zheng, Y. Le, A. P. C. Chan, Y. Hu, and Y. Li, "Review of the application of social network analysis (SNA) in construction project management research," *International Journal of Project Management*, vol. 34, no. 7, pp. 1214–1225, 2016.

[47] P. A. Gloor, A. Fronzetti Colladon, F. Grippa, and G. Giacomelli, "Forecasting managerial turnover through e-mail based social network analysis," *Computers in Human Behavior*, vol. 71, pp. 343–352, 2017.

[48] C. Z. Li, J. Hong, F. Xue, G. Q. Shen, X. Shen, and M. K. Mok, "Schedule risks in prefabrication housing production in Hong Kong: a social network analysis," *Journal of Cleaner Production*, vol. 134, pp. 482–494, 2016.

[49] N. M. Tichy, M. L. Tushman, and C. Fombrun, "Social network analysis for organizations," *The Academy of Management Review*, vol. 4, no. 4, pp. 507–519, 1979.

[50] A. W. Wolfe, "Social network analysis: methods and applications," *American Ethnologist*, vol. 24, no. 1, pp. 219-220, 2010.

[51] J. C. Mitchell, *Social Networks in Urban Situations: Analyses of Personal Relationships in Central African Towns*, Manchester University Press, Manchester, UK, 1969.

[52] K. Y. Mok, G. Q. Shen, and J. Yang, "Stakeholder management studies in mega construction projects: a review and future directions," *International Journal of Project Management*, vol. 33, no. 2, pp. 446–457, 2015.

[53] J. G. Shi, H. Y. Si, G. D. Wu, Y. Y. Su, and J. Lan, "Critical factors to achieve dockless bike-sharing sustainability in China: a stakeholder-oriented network perspective," *Sustainability*, vol. 10, no. 6, 2018.

[54] T. Yu, G. Q. Shen, Q. Shi, X., C. Z. Lai, and K. Xu, "Managing social risks at the housing demolition stage of urban redevelopment projects: a stakeholder-oriented study using social network analysis," *International Journal of Project Management*, vol. 35, no. 6, pp. 925–941, 2017.

[55] S. Brinkmann, "Interview," in *Encyclopedia of Critical Psychology*, pp. 1008–1010, Springer, Berlin, Germany, 2014.

[56] S. Christensen, J. McNamara, and K. O'Shea, "Legal and contracting issues in electronic project administration in the construction industry," *Structural Survey*, vol. 25, no. 3/4, pp. 191–203, 2007.

[57] D. Thompson and R. G. Miner, "Building information modeling-bim: contractual risks are changing with technology," 2006, http://www.aepronet.org/ge/no35.html.

[58] E. Alreshidi, M. Mourshed, and Y. Rezgui, "Factors for effective BIM governance," *Journal of Building Engineering*, vol. 10, pp. 89–101, 2017.

[59] H. Yan and P. Demian, *Benefits and Barriers of Building Information Modelling*, 2008.

[60] G. Aranda-Mena, J. Crawford, A. Chevez, and T. Froese, "Building information modelling demystified: does it make business sense to adopt BIM?," *International Journal of Managing Projects in Business*, vol. 2, no. 3, pp. 419–434, 2009.

[61] B. D'Agostino, M. Mikulis, and M. Bridgers, *FMI/CMAA Eighth Annual Survey of Owners: The Perfect Storm–Construction Style, FMI/CMAA*, 2007.

[62] K. Bentley and B. Workman, "Does the building industry really need to start over," in *A Response from Bentley to Autodesk's BIM/Revit Proposal for the Future (White Paper), Bentley*, 2003.

[63] R. Sebastian, "Breaking through business and legal barriers of open collaborative processes based on building information modelling (BIM)," in *Proceedings of CIM World Building Congress*, pp. 166–186, Salford Quays, UK, April 2010.

[64] M.-H. Construction, "The business value of BIM in North America: multi-year trend analysis and user ratings (2007-2012)," 2012. Smart Market Report.

[65] H. Lindblad, "*Study of the implementation process of BIM in construction projects/analysis of the barriers limiting BIM adoption in the AEC-industry*," vol. 633132, M.S. Thesis, University of Stockholm, Stockholm, Sweden, 2013, http://kth.diva-portal.org/smash/get/diva2.

[66] J. Jia and X. J. Y. He, *Statistics*, China Renmin University Press, Beijing, China, 2012.

[67] R. J. Yang and P. X. W. Zou, "Stakeholder-associated risks and their interactions in complex green building projects: a social network model," *Building and Environment*, vol. 73, no. 1, pp. 208–222, 2014.

[68] S. Wasserman and K. Faust, "Social network analysis: methods and applications," *Contemporary Sociology*, vol. 91, no. 435, pp. 219-220, 1995.

[69] P. Knauber, D. Muthig, K. Schmid, and T. Widen, "Applying product line concepts in small and medium-sized companies," *IEEE Software*, vol. 17, no. 5, pp. 88–95, 2000.

[70] D.-X. Zhao, B.-J. He, C. Johnson, and B. Mou, "Social problems of green buildings: from the humanistic needs to social acceptance," *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 1594–1609, 2015.

[71] R. Kreider, J. Messner, and C. Dubler, "Determining the frequency and impact of applying BIM for different purposes on projects," in *Proceedings of the 6th International Conference on Innovation in Architecture, Engineering and Construction (AEC)*, pp. 9–11, Loughborough, UK, January 2010.

[72] A. H. Abd Jamil and M. S. Fathi, "Contractual challenges for BIM-based construction projects: a systematic review," *Built Environment Project and Asset Management*, vol. 8, no. 4, pp. 372–385, 2018.

[73] J. Won, G. Lee, C. Dossick, and J. Messner, "Where to focus for successful adoption of building information modeling within organization," *Journal of Construction Engineering and Management*, vol. 139, no. 11, article 04013014, 2013.
[74] D. C. Kent and B. Becerik-Gerber, "Understanding construction industry experience and attitudes toward integrated project delivery," *Journal of Construction Engineering and Management*, vol. 136, no. 8, pp. 815–825, 2010.
[75] R. Maskil-Leitan and I. Reychav, "A sustainable sociocultural combination of building information modeling with integrated project delivery in a social network perspective," *Clean Technologies and Environmental Policy*, vol. 20, no. 5, pp. 1–16, 2018.
[76] C. Boton and D. Forgues, "Practices and processes in BIM projects: an exploratory case study," *Advances in Civil Engineering*, vol. 2018, Article ID 7259659, 12 pages, 2018.
[77] J. E. Taylor and R. Levitt, "Innovation alignment and project network dynamics: an integrative model for change," *Project Management Journal*, vol. 38, no. 3, pp. 22–35, 2007.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 3721397, 14 pages
https://doi.org/10.1155/2019/3721397

Research Article

Project Benefits of Digital Fabrication in Irregular-Shaped Buildings

Namhyuk Ham [1] and Sanghyo Lee [2]

[1]*Department of Digital Architectural and Urban Engineering, Hanyang Cyber University, 220 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[2]*Division of Architecture and Civil Engineering, Kangwon National University, Samcheok 25913, Republic of Korea*

Correspondence should be addressed to Sanghyo Lee; leesh0903@kangwon.ac.kr

Received 7 August 2018; Revised 20 November 2018; Accepted 13 December 2018; Published 20 January 2019

Academic Editor: Mohammad R. Hosseini

The main purpose of this study is to investigate the advantages of digital fabrication pertaining to construction project management, in particular, in terms of different project management factors, using case studies of irregular-shaped buildings in which digital fabrication has versatile applications. This study collected secondary data corresponding to 27 construction projects of irregular-shaped buildings that implemented digital fabrication. Success criteria were developed based on the Project Management Body of Knowledge (PMBOK) to assess the benefits of implementing digital fabrication for management of the considered construction projects of irregular-shaped buildings. Content analysis was performed to investigate the degree of satisfaction for the success criteria of each project. With this approach, it is possible to see which success criterion appears more times as a positive factor and which ones appear as challenges or problems. Among the positive benefits of digital fabrication on construction project management, quality increase and control appeared in the highest number of projects (17 out of 27 projects) at the highest frequency (26 instances). However, among the negative benefits that were mentioned as challenging or causing difficulties of digital fabrication on construction project management, cost reduction and control appeared in the highest number of projects (14 out of 27 projects) at the highest frequency (21 instances). But it does not mean that the use of digital fabrication was overall negative.

1. Introduction

The construction industry is responsible for up to 40% of energy consumption and greenhouse gas emission worldwide [1]. For such reasons, major international organizations (e.g., UNEP and IPCC) consider the construction industry as the main governing factor for carbon reduction activities [2]. This potential can be employed by implementing modern technologies including digital technology in place of traditional construction methods [3]. Digital technology is used widely in the manufacturing industry, and the method of directly manufacturing construction components using design data has become an essential part in recent product development [4]. However, the construction industry has an extremely disjointed production method, and since it is a risk-averse sector, manufacturing using digital technology still remains in the preliminary stages [5]. Not only do most construction companies lack resources to develop innovative technology through projects [6] but they also fail to systemize the developed knowledge, and therefore avoid using unfamiliar material and manufacturing methods [7].

Despite this, interest in irregular-shaped buildings with considerably complicated structures compared to typical buildings is continuously growing [8]. An irregular-shaped building is used mainly in terms of "irregular-shaped buildings [8, 9]," "freeform building [10, 11]," "informal structure [12]," "complex-shaped buildings [13]," and "iconic building [14]." In general, it refers to a building to which an irregular design element such as a two-direction curved surface is applied to the interior or exterior of the building.

It is common to introduce digital fabrication with new materials and manufacturing methods in such irregular-shaped buildings to construct the complicated structures [15]. Digital fabrication represents innovative, computer-controlled processes and technologies with the potential to expand the boundaries of conventional construction [6]. When it comes to project management, implementing digital fabrication requires managing not only the conventional supply chain but also supply chains for the new manufacturing methods [16]. Moreover, construction sites require managing the typical on-site construction as well as off-site construction and off-site and on-site deliveries [17]. Furthermore, in order to attend to problems that occur while constructing irregular-shaped buildings, various digital technologies are used including building information modeling (BIM) [18], reverse engineering with 3D laser scanning [19], computer-aided manufacturing (CAM) and computer-aided engineering (CAE) [4], and computerized numerical control (CNC) [20]. Such digital technologies directly support optimized design, factory production of construction segments from design data, and site assembly and installation; increase the quality of irregular-shaped buildings; and reduce the construction period and cost [21].

The number of studies analyzing the effects of digital fabrication on sustainability is gradually increasing [22–24]. However, studies that quantitatively analyze the types of positive and negative effects that digital fabrication has on construction project management are hard to find. Thus, this study aims at constructing theoretical evidence concerning the effect of digital fabrication on construction projects through preliminary analyses of changes in the manufacturing paradigm and effects of digital fabrication on sustainability. Based on this, case studies on irregular-shaped buildings implemented with digital fabrication are investigated to quantitatively evaluate the benefits of digital fabrication for construction project management.

2. Literature Review

2.1. Trend of Manufacturing Paradigms. The manufacturing paradigm started from a very slow process of manual crafting. Mass production became possible through the industrial revolution in the early 20th century, and the manufacturing system has greatly evolved economically through endless technology development. Lean manufacturing allowed the mass production of standardized products with high quality [4]. Additionally, allocation for manufacturing reduced in size to allow customization [25]. This mass customization started with split demands from customers for high-quality low-cost products and the niche market for such products. A new trend of manufacturing is mass personalization. Products are created within the mass customization framework and include distinctive features according to the consumers. This trend closely resembles mass customization, but the niches are different in nature. Therefore, manufacturing systems must be flexible to meet such demands [26].

In supporting this trend, additive manufacturing (AM) processes such as rapid prototyping and stereolithography play an important role in reducing the time and cost of development required for assessing designs using prototypes [27]. AM does not require formulating a processing plan before manufacturing, but rather, it manufactures artifacts (defined geometrically) directly derived from 3D CAD models. A large amount of AM-type technology started to develop in the 1980s including 3D printing. This manufacturing method leads many industries to the concept of direct digital manufacturing (DDM). The current manufacturing methods for products are redefined using DDM. Components are no longer manufactured in factories and then assembled to create the final product before being delivered to clients. Instead, these products are manufactured in close proximity to the clients using AM based on digital models [27]. Therefore, AM is evolving into DDM as a mutual link for computers and manufacturing software through manufacturing equipment and network (e.g., Internet and servers). Various forms of DDM have the potential for changing the efficiency of materials for product business models, process chain, and relationship with product consumers [4]. Furthermore, it is also possible to combine the advantages of such a production paradigm to produce customized high-quality products.

Such changes in the production paradigm in the construction industry can be seen through the gradual increase in the number of large-scale irregular-shaped buildings with very complex structures. Irregular-shaped buildings face limitations, in which conventional construction materials and production methods cannot be applied effectively owing to the structural constraints. Moreover, construction projects are fundamentally involved with one-off teams based on a disjointed production system. Because the product size is large compared to that in the manufacturing industry, customization in advance is difficult. Consequently, digital fabrication is gradually being introduced to overcome the fundamental problems of a conventional production system. However, studies that analyze the effects of digital fabrication on actual construction projects are rare. In particular, a performance indicator for construction project management, which can be used by construction firms trying out the new manufacturing paradigm of digital fabrication, is not yet available. Therefore, this study aims at suggesting key performance indicators (KPIs) for assessing the benefits of digital fabrication for construction projects and verifying them through case studies.

2.2. Digital Fabrication for Sustainability. Recent studies have emphasized the benefits that AM brings regarding sustainability [28, 29]. However, these studies mostly focus on small-scale processes. For example, Kreiger and Pearce proved that distributed manufacturing through 3D printing potentially had lesser environmental impact and energy consumption compared to the conventional manufacturing method [22]. Faludi et al. pointed out that 3D printing could reduce processing efforts, which could eventually reduce the waste and energy consumption compared to that in conventional CNC milling [23]. Gebler et al. provided a general perspective on 3D printing technology from environmental, economic, and social perspectives [24]. However, quantitative studies were rarely found among these studies, and Ford and Despeisse stressed that significantly more applied studies on the environmental impacts of digital fabrication were required [28]. Agustí-Juan et al. evaluated the potential environmental benefits from applying conventional manufacturing and digital fabrication on different types of concrete walls in order to quantify environmental benefits that digital fabrication could bring to the construction industry [6].

A new manufacturing method that clearly distinguishes itself from conventional production methods in the construction industry is digital fabrication, which is based on various digital technologies [6]. In the construction industry, digital fabrication is implemented through particular projects such as irregular-shaped buildings. It is through these particular construction projects that manufacturing processes superior to conventional manufacturing methods are developed from design aspirations and technological innovations [30]. Digital fabrication processes in the construction industry are based on computational design methods and robotic construction processes. In particular, irregular-shaped building segments are typically achieved by combining materials of additional manufacturing processes (e.g., assembly, lamination, extrusion, and other forms of 3D printing) using industrial robots [31]. Using this digital fabrication, technology has allowed the construction of customized complex buildings [32].

However, questions still prevail concerning the positive benefits for sustainability in the manufacturing sector wherein digital fabrication is applied. Traditionally, the performance of a production system in the manufacturing stage was evaluated by monitoring four main factors: cost, time, quality, and flexibility. However, additional elements that are an integral part of sustainability such as energy and resource efficiency must be considered, as shown in Figure 1 [33]. It is evident that sustainability has conjoined with cost and evolved as a main decision-making factor in manufacturing [4].

Digital fabrication is a technology that is crucial for the construction industry for constructing irregular-shaped buildings, but it cannot be regarded as the only system that is required for constructing buildings. Currently, real-life projects have a basis in conventional manufacturing and only apply digital fabrication to limited building segments. Lean construction refers to applying the concept and principles of the Toyota Production System (TPS) to construction fields and focuses on waste reduction, increase in customer value, and continuous improvement [34]. Lean construction is possible through the integrated project delivery (IPD) approach, and BIM is essential in effectively carrying out collaborations required for an IPD [35] and contributing in sharing data necessary for achieving lean construction [36]. Bryde et al. quantitatively evaluated the benefits of BIM for construction project management [37]. As such, benefits of digital fabrication for construction projects in the construction industry must be evaluated with a focus on its effects on the overall construction project management rather than the sustainability of manufacturing technologies.

2.3. Limitation of Assessment for Benefits of Digital Fabrication. Sustainability is the latest main interest in many industries [38, 39]. The KPIs related to sustainability allow manufacturers to monitor and evaluate all essential aspects including economic, social, and environmental factors [40, 41]. Many studies have tried evaluating sustainability for manufacturing systems and the life span of products [42]. Moreover, numerous tools were developed to support sustainable manufacturing including green supply chains, reverse logistics, design for environment, and design for disassembly [33, 43–45].

However, studies evaluating the sustainability aspects of particular technologies of AM and DDM are very limited in terms of their findings [46–48]. Consequently, tools that allow the quantitative analysis of the benefits of digital fabrication for construction projects are rarely attainable. Moreover, although digital fabrication is a very important technological element in attaining the quality of irregular-shaped buildings, it cannot replace the entire system necessary for constructing buildings. To this day, real construction projects typically adopt the conventional manufacturing method and apply digital fabrication only to specific segments.

Understanding the potential benefits of digital fabrication through projects is a challenge that must be addressed. By implementing new manufacturing technologies such as digital fabrication, changes occur in the roles of key parties (e.g., clients, architects, contractors, subcontractors, and suppliers) in a construction project, contract relations, and reengineered collaborative processes [49]. Specifically, construction project managers must undertake more managing tasks than before if digital fabrication is implemented. However, the ultimate effects of introducing a new manufacturing technology on the daily managing tasks of a construction project manager and project outcomes still remain unclear [50]. Moreover, it is uncertain whether a new manufacturing technology will be able to overcome the operational problems that arise from the disjointed nature of the construction industry [51]. Thus, this study aims at evaluating the benefits of using digital fabrication for construction project management through data collection of irregular-shaped buildings. The research method for this task is explained in the next section.

3. Research Method

3.1. Secondary Data Collection. In order to investigate the type of benefits of digital fabrication on construction project management, secondary data for irregular-shaped buildings in which digital fabrication was employed were collected. Empirical studies on tasks related to construction project management often use self-reported data [37]. However, an alternative approach using secondary data has the benefit of reducing inaccuracy that arises from self-reporting and accessing data on an event [52]. The secondary data of this study were collected from projects using digital fabrication utilizing innovative computer control processes and technologies. The sources of secondary data on overseas projects were collected through the AIA BIM TAP Awards

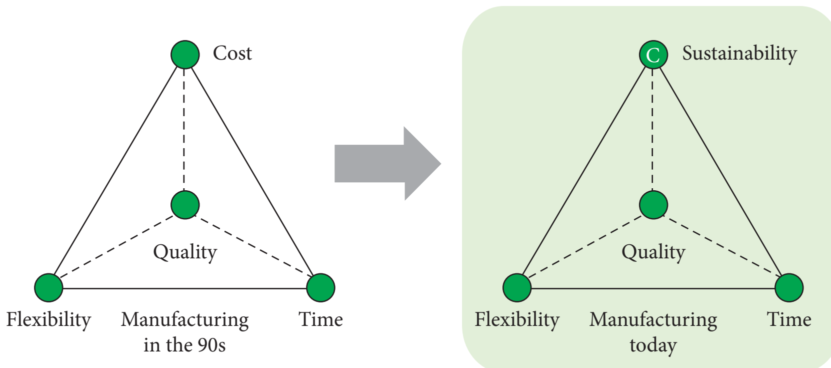


Figure 1: Manufacturing decision-making attributes in the 1990s and at the present time [27].

(currently, AIA/TAP Innovation Awards Program) from 2005 to 2017 on irregular-shaped buildings that had implemented digital fabrication [53]. And the sources of secondary data on projects in Korea were collected through the previous research data of Korean BIM Journal (e.g., the BIM Vol. 1~12, KIBIM Magazine 2011~2016) and Korean BIM Award (e.g., Autodesk Korea BIM Awards 2014, Building Smart Korea BIM Award 2009~2015) [54]. Data were supplemented from information available through public domains such as academic journals and conference publications, design firms and construction firms of each project, and manufacturing firms that directly manufactured irregular-shaped members. This was done in order to improve reliability of the secondary data. Furthermore, professional interviews were carried out for actual workers in digital fabrication to add overlooked study cases on irregular-shaped buildings and to verify the collected secondary data.

Twenty-seven study cases on irregular-shaped buildings that mentioned positive and negative benefits of adapting digital fabrication were selected for further analyses. In order to evaluate the project advantages of digital fabrication in terms of the management of construction projects, case projects were selected considering the characteristics of the project. In other words, we selected a project to investigate the characteristics (e.g., an area of irregular-shaped segments, a number of unit materials, a size of unit material, a production method, and segments with irregular shapes) of digital fabrication. On the other hand, we excluded projects where the project size was small, or digital fabrication was applied only to some sections and did not bring significant benefits to construction projects.

3.2. Success Criteria. Evaluation criteria were established to analyze data on the types of benefits introduced due to digital fabrication, or if any benefits were introduced at all. This analysis was performed by deriving a "success criteria" that met the goals for time, cost, and quality of construction projects and was related to process management aspects including effective scope management and communications. These success criteria reflected the idea of multidimensional success of construction projects by including not only the projects themselves but also project management [55]. The success criteria can also be referred to as "critical success factors" or "key results areas" in project management [37].

The success criteria were classified according to the Project Management Body of Knowledge (PMBOK) knowledge areas of the Project Management Institute (PMI) in order to establish the evaluation standards for the positive and negative benefits of digital fabrication for construction projects [56]. These knowledge areas were chosen as they provided an upper framework that was inclusive of all aspects of success in a project [37]. As shown in Table 1, the success criteria were used to compare the roles and benefits of digital fabrication on irregular-shaped buildings with those expected from a project manager.

3.3. Content Analysis. It is very difficult to objectively evaluate the impact of digital fabrication on construction projects. However, researchers have difficulty in securing the expert pool by applying digital fabrication to the irregular-shaped buildings, and even if they have a pool of experts, interviews and expert interviews are limited. In this regard, Bryde et al. analyzed the project benefits of BIM on construction projects through content analysis of secondary data [37].

A content analysis process suggested by Harris was carried out to confirm the positive and negative benefits of digital fabrication for construction projects using secondary data for each irregular-shaped building. The unit of analysis adopted was the "phrase," which may vary from a single word to a whole sentence [52]. The phrase in this study refers to "project benefit" [37]. The phrase associated with "project benefit" found in each study case of irregular-shaped buildings was converted into the success criteria, as shown in Table 1. During the conversion process, the phrase related to procurement or stakeholder was rarely found among the success criteria. Consequently, the two factors, procurement and stakeholder, were omitted, and instead, software issues and materials of irregular-shaped segments were added as important factors related to the quality of irregular-shaped segments during content analysis for applying digital fabrication.

The projects were then organized using the added score for each of them (positive benefits minus negative benefits). This is not an attempt to find which case demonstrates the

Table 1: Success criteria based on PMBOK knowledge area.

PMBOK knowledge area	Definition (after PMI, 2013)	Criterion	Positive consideration
Integration management	Unification, consolidation, articulation, and integrative actions	Integration	Improvement
Scope management	Defining and controlling what is and is not included in the project	Scope	Clarification
Time management	Manage the timely completion of the project	Time	Reduction or control
Cost management	Planning, estimating, budgeting, financing, funding, managing, and controlling costs	Cost	Reduction or control
Quality management	Quality planning, quality assurance, and quality control	Quality	Increase or control
Human resource management	Organize, manage, and lead the project team	Organization	Improvement
Communication management	Timely and appropriate planning, collection, creation, distribution, storage, retrieval, management, control, monitoring, and the ultimate disposition of project information	Communication	Improvement
Risk management	Increase the likelihood and impact of positive events and decrease the likelihood and impact of negative events in the project	Risk	Negative risk reduction
Procurement management	Purchase or acquire the products, services, or results needed from outside the project team	Procurement	Help
Stakeholder management	Develop appropriate management strategies for effectively engaging stakeholders in project decisions and execution	Stakeholder	Satisfaction

most beneficial use of digital fabrication but to organize the data in a way that highlights were there are more positive than negative benefits. Hence, the numbers on the score column should not be seen as an indicator of how successful or unsuccessful those case study projects were, but simply how many success criteria were mentioned positively or negatively [37]. For example, the case study of P6 (Lotte World Tower Podium) in Table 3 shows that the cost-based success criterion is "−2" and the risk-based success criterion is "−1." This means that there are two aspects of the digital fabrication related to the cost, risk success, and criteria that were mentioned as challenging or causing difficulties (negative benefit) but it does not mean that the use of digital fabrication was overall negative. With this approach, it is possible to see which success criterion appears more times as a positive factor and which ones appear as challenges or problems.

4. Assessment of Project Benefits of Digital Fabrication

4.1. Case Description. Table 2 summarizes the study cases where digital fabrication was applied to the construction of irregular-shaped buildings. The total area, area of irregular-shaped segments, material of irregular-shaped segments, number of unit material, size of unit material, production method, segments with irregular shapes (interior/exterior), construction work, construction period, and software were collected as data. Any data that were difficult to collect were supplemented through interviews of professionals from firms specializing in digital fabrication. Among the 27 projects from the study cases, 11 projects had irregular-shaped segments comprising an area of 10,000 m^2 and 4 projects had an area of 50,000 m^2. Irregular-shaped segments for which digital fabrication was applied were classified into interior and exterior. Digital fabrication was applied on the interior (4%) in 1 project, on the exterior (85%) in 23 projects, and on the interior and exterior (11%) in 3 projects. The results for construction work were similar to that for the irregular-shaped segments. Of all the projects, 26 (96%) corresponded to curtain wall and exterior finishing work, while 1 (4%) corresponded to interior finishing work. Various types of materials were used for irregular-shaped segments including those commonly used in conventional construction projects; for example, steel, concrete, aluminum, glass, ethylene tetrafluoroethylene (ETFE), polytetrafluoroethylene (PTFE), glass fiber-reinforced polymer (GFRP), glass fiber-reinforced concrete (GFRC), and ultrahigh performance concrete (UHPC). The production method for irregular-shaped segments differed according to material.

A CNC machine was used to produce AL. panels, AL. bars, wood panels, titanium panels, and molds, and the members were directly manufactured through cutting, welding, and milling. Materials such as concrete panels, UHPC, and customized bricks were produced into members using an irregular-shaped formwork manufactured with a CNC machine. For a unique material such as ETFE, members are produced using pressure. AL. panels were produced using conventional materials with the latest machine multipoint stretching forming (MDSF) machine depending on the design. High-end software such as CATIA, which can minimize the error range in the production, was found to be used frequently for digital fabrication to ensure the quality of the irregular-shaped segments.

4.2. Positive and Negative Benefits of Using Digital Fabrication. Table 3 summarizes the evaluation results of the benefits of digital fabrication for construction project management

Table 2: Details of cases.

PJT no.	PJT name (city/country)	Total area (m^2)	Irregular-shaped segments (m^2)	Irregular-shaped segment material	Number of members	Fabrication method	Interior/exterior	Member size	Work type	Construction Period	Software
P1	GT tower (Seoul/Korea)	54,583	19,000	AL. BAR glass	22,000 EA 12,500 EA	CNC machine	Exterior	1,400/1,450 mm × 4,500/6,000/7,000 mm 1,400/1,450 mm × 550/1,100 mm	Curtain wall	12 months*	CATIA
P2	Tri bowl (Incheon/Korea)	2,893	3,012	AL. panel	2,308 EA	CNC machine	Exterior	1,600 mm × 800 mm	Exterior finish	8 months*	CATIA, Rhino
P3	DDP (Seoul/Korea)	83,024	33,228	AL. panel	45,133 EA	CNC machine and MDSF	Exterior	1,600 mm × 1,200 mm	Exterior finish	14 months*	CATIA, Rhino, TEKLA
P4	Ecorium (Seocheon/Korea)	33,091	9,628	Glass	32,093 EA	CNC machine	Exterior	540 mm × 540 mm	Steel curtain wall	24 months*	CATIA
P5	Theme Pavilion of Yeosu EXPO (Yeosu/Korea)	7,414		GFRP	98 EA	CNC machine and MDSF	Exterior		Exterior finish	20 months*	CATIA
P6	Lotte World tower Podium (Seoul/Korea)	328,351	8,181	NT panel AL. BAR	17,934 EA 11,791 EA	CNC machine	Interior	1000 mm × 200 mm	Interior finish	10 months*	CATIA
P7	The Arc (Daegu/Korea)	5,963	1,991	ETFE	336 EA	CNC machine	Exterior	3,000 mm × 2,500 mm	Steel exterior finish	5 months*	CATIA
P8	KEB HANA Bank (Seoul/Korea)	16,287	3450	UHPC	256 EA	CNC machine and mold	Exterior	2,000 mm × 4,200/4,400/6,200 mm	Exterior finish	12 months*	CATIA
P9	Korea National Maritime Museum (Busan/Korea)	25,803				CNC machine	Exterior		Curtain wall		TEKLA
P10	BEAT360 (Seoul/Korea)	1,880		Al. panel Wood panel	7,553 EA; 8,800 EA	CNC machine	Interior/exterior		Interior/exterior finish		
P11	Denver Art Museum (Denver/USA)	13,564	16,538	Titanium panel	9,000 EA	CNC machine	Exterior	2,100 mm × 800 mm	Exterior finish	39 months	CATIA, TEKLA
P12	Water Cube (Beijing/China)	90,000	52,000	ETFE	4,000 EA	CNC machine and pressure	Exterior	Diameter-7,500 mm Circle	Steel exterior finish	50 months	Rhino, 3D MAX, Microstation
P13	Bird's Nest (Beijing/China)	260,000	38,500 53,000	ETFE PTFE	884 EA 1,044 EA	CNC machine and pressure	Exterior		Steel exterior finish	46 months	TEKLA
P14	Basra Sports City (Basra/Iraq)		65,000	GFRP	560 EA	Mold	Exterior	Length: 300,000 mm	Exterior finish	53 months	CATIA, TEKLA
P15	Louis Vuitton Foundation (Paris/France)	11,000	13,500 9,000	Concrete Glass	19,000 EA 3,600 EA	CNC machine and MSV	Exterior	3,000 mm × 1,500 mm 1,500 mm × 400 mm	Exterior finish	74 months	CATIA
P16	Louisiana State Museum and Sports Hall of fame (Natchitoches/USA)	28,000	1,380	Cast Stone panel	1,150 EA	CNC machine	Interior/exterior	2,000 mm × 500 mm	Interior/exterior finish		Navisworks
P17	Hangzhou Sports Park Stadium (Hangzhou/China)	400,000	15,000	AL. Panel	55 EA	CNC machine	Exterior	Height: 12 m–18 m	Exterior finish	84 months	Grasshopper
P18	Perot Museum of Nature and Science (Dallas/USA)	180,000	9,300	Concrete steel	700 EA 8,400 EA	CNC machine and mold	Exterior	9,200 mm × 2,400 mm	Exterior finish	31 months	REVIT

Table 2: Continued.

PJT no.	PJT name (city/country)	Total area (m^2)	Irregular-shaped segments (m^2)	Irregular-shaped segment material	Number of members	Fabrication method	Interior/ exterior	Member size	Work type	Construction Period	Software
P19	Phoenix Biomedical Campus: Health Sciences Education Building (Phoenix/USA)	24,898	8,910	Copper panel	6,000 EA	Press brake-punch-and-die machine	Exterior	3,300 mm × 300/450/760 mm	Exterior finish	27 months	REVIT
P20	Zlote Tarasy (Warszawa/Poland)	205,000	10,240	Glass Steel	4,788 EA 7,123 EA	CNC machine	Exterior	2.14 ㎡ per panel	Exterior finish	52 months	
P21	Weltstadthaus (Cologne/Germany)	14,400	4,900	Glass	6,800 EA	CNC machine	Exterior	0.72 ㎡ per a panel	Exterior finish	72 months	
P22	BMW Welt (Munich/Germany)	16,500	8,000	Glass	4,500 EA	CNC machine	Interior/exterior	2.22 ㎡ per a module	Interior/exterior finish	56 months	Nemetschek Allplan
P23	Museo Soumaya (Mexico City/Mexico)	16,000		Steel	16,000 EA	CNC machine	Exterior	630 mm hexagon	Exterior finish	38 months	CATIA
P24	O-14 tower (Dubai/UAE)	28,000		Concrete		CNC machine and mold	Exterior		Exterior finish	48 months	Rhino, SAP2000
P25	Qatar National Museum (Doha/Qatar)	47,000	120,000	GFRC	75,000 EA	Mold	Exterior	400 m × 250 m per disc	Exterior finish	72 months	CATIA
P26	University of technology Sydney (Sydney/Australia)	16,030	5,594	Customized brick	320,000 EA	Mold	Exterior	Brick: 76 mm × 110 mm × 230 mm	Exterior finish	24 months	REVIT
P27	Benz Museum (Stuttgart/Germany)	16,500	6,171 5,289	Glass AL. Panel	1,800 EA 1,000 EA	Mold	Exterior		Exterior finish	36 months	

Table 3: Positive and negative benefits of using digital fabrication on selected cases.

Project	Integ.		Scope		Time		Cost		Qual.		Org.		Com.		Risk		Soft.		Mat.		Score
	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	
P1								−1	1							−1	1				0
P2	1		1						1								1				4
P3	1							−2	2		1				1		2				5
P4																	1				1
P5					1				1								1				3
P6	2				1			−2	2		1		1			−1	1		1		6
P7	1				1			−2	1								1		2		4
P8	2				1			−1	2								1		1		6
P9						−1									1		1				1
P10															1						1
P11	1				1			−2	1							−1	2				2
P12	2							−1	1				1						1		4
P13	1							−2	2								1		2		4
P14								−2									2		1		1
P15	1								2						2		2				7
P16	1				1				1								1		1		5
P17						−1		−1											1		−1
P18	1								1		1		1								4
P19																			1		1
P20								−1													−1
P21	1					−1						−1									−1
P22			1			−2			2		2										3
P23			1					−1									1		1		2
P24			1		1			−1											1		2
P25								−2	1								1		1		1
P26	2					−1	1		3						2			−1	2		8
P27									2												2
Total	17	0	4	0	7	−6	1	−21	26	0	5	−1	3	0	7	−3	20	−1	16	0	74
Average	0.63	0.00	0.15	0.00	0.26	−0.22	0.04	−0.78	0.96	0.00	0.19	−0.04	0.11	0.00	0.26	−0.11	0.74	−0.04	0.59	0.00	2.74

obtained using 10 success criteria. The benefits of digital fabrication for construction project management were evaluated by subtracting the negative benefits from the positive benefits in order to obtain a score for each case study. This is shown in the score column in Table 3.

The focus of evaluation was not on how effectively each case study used digital fabrication but on highlighting the positive benefits over the negative benefits. Therefore, the values in the score column in Table 3 do not serve as an index to determine the success of a project. These values simply indicate how many success criteria were mentioned positively and negatively from the secondary data of projects in the case studies. For example, case study P17 (Hangzhou Sports Park Stadium) expressed a negative experience owing to its challenges or difficulties with respect to time and cost, while a positive experience was observed in terms of material caused by achieving good quality irregular-shaped segments. Case study P20 (Zlote Tarasy) presented a negative experience in applying digital fabrication owing to its challenges or difficulties in terms of cost. Case study P21 (Weltstadthaus Cologne) expressed a negative experience in applying digital fabrication owing to its challenges or difficulties in terms of time and organization, while a positive experience was seen in terms of integration from digital fabrication. While the subtotal score of case studies P17, P20, and P21 was "−1," this neither implies that introducing digital fabrication created losses in terms of construction project management nor that they were failed projects. Furthermore, the scores of positive and negative benefits for the case studies were not combined for each success criterion but divided into two separate columns (positive benefits and negative benefits), as listed in Table 3. This approach showed the success criteria that appeared more frequently as a positive element, which were challenges to be tackled, and what type of problems they had.

4.3. Success Criteria Ranking of Using Digital Fabrication. Each success criterion was defined with the frequency of occurrence for positive and negative benefits (Table 4) and was ranked according to the summation of total instances and the total number of projects for positive benefits. Moreover, the total instances and total number of projects for negative benefits were shown together. An approach for quantifying the number of projects in which a success criterion had an influence as a positive benefit is fundamentally conservative [37]. In some cases, a success criterion was mentioned once in a positive manner and once in a negative manner. In such a situation, the success criteria were not counted as projects that had a positive effect (or negative), regardless of the impact of the project on the outcome. For example, on the Louis Vuitton Foundation, described by AIA TAP BIM Award, the integration success criterion was counted once as positive for the "Integration of construction modifications in the 3D model" and the quality success criterion was counted once as positive for the "Construction quality was monitored with on-site with laser equipment, and round-tripped back into the model [57]."

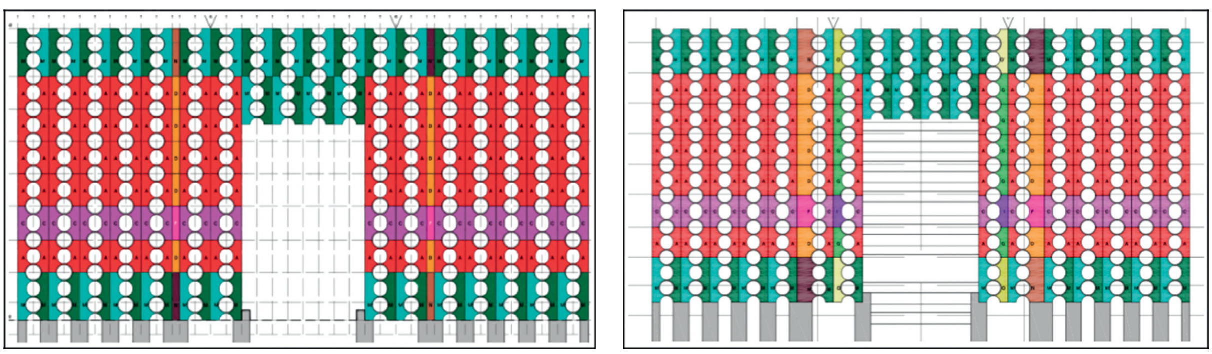
4.3.1. Quality Success Criterion. There were a total of 26 instances of positive benefits in terms of quality increase or control from applying digital fabrication in 17 (63%) projects; the negative benefits were not observed. Digital fabrication can evaluate constructability starting from the design stage to allow optimum design, as well as use latest equipment such as a CNC machine, MDSF, and MSV that allow precise production and minimize error down to the millimeter range to achieve the quality required for construction projects. Case study P25 (National Museum of Qatar) included quality standards for irregular-shaped segments in the request for proposal (RFP) [58–61]. This document includes "design and engineering methodology," "design optimization," "fabrication of panels," and "methodology of survey works" for irregular-shaped segments.

4.3.2. Software Issues Success Criterion. Positive benefits in terms of software issues from implementing digital fabrication were mentioned in 20 instances in 16 (59%) projects; a negative benefit was observed in one instance owing to the lack of experience in high-end software programming. Digital fabrication executes design, manufacture, and construction based on 3D models. Thus, software was used to generate 3D models in all studied projects. Most projects found positive benefits from using high-end software such as CATIA and TEKLA because it minimized error ranges in the manufacturing of irregular-shaped segments. In addition, a positive benefit of being able to swiftly and continuously provide necessary manufacturing information to the manufacturers by obtaining tens of thousands of 2D manufacturing blueprints from 3D models in a short period of time was observed [62]. Furthermore, collaboration, clash detection, and supply calculation were possible using 3D models. Although high-end software can support global collaboration systems based on server networks [63], the applicability is not up to par. This is because not all participants in the supply chain related to digital fabrication have the resources to use high-end software.

4.3.3. Integration Success Criterion. Positive benefits in terms of integration improvement from applying digital fabrication were seen in 17 instances in 13 (48%) projects; negative benefits were not indicated. The integration process of increasing productivity by optimizing different and individually designed members from simultaneously considering design, manufacture, and construction is crucial for irregular-shaped buildings. Decisions on member size and production unit that consider materials and production methods were made by optimizing the design of irregular-shaped buildings. The design optimization results for irregular-shaped segments for case study P8 (KEB Hana Bank, Samsung-dong, Seoul) are shown in Figure 2 [64]. Irregular-shaped segments can increase the construction cost or affect the construction period in the case of many types of formwork being presented according to unit size, and thus increasing the manufacturing time of the FRP formwork. Projects in the case studies minimized the number of mold types for formwork from 12 in the initial

Table 4: Success criteria ranking of using digital fabrication.

Success criterion	Positive benefit			Negative benefit		
	Total instances	Total number of projects	% of total projects	Total instances	Total number of projects	% of total projects
Quality increase or control	26	17	62.96	0	0	0.00
Software issues	20	16	59.26	1	1	3.70
Integration improvement	17	13	48.15	0	0	0.00
Material improvement	16	13	48.15	0	0	0.00
Negative risk reduction	7	5	18.52	3	3	11.11
Time reduction or control	7	7	25.93	6	5	18.52
Organization improvement	5	4	14.81	1	1	3.70
Scope clarification	4	4	14.81	0	0	0.00
Communication improvement	3	3	11.11	0	0	0.00
Cost reduction or control	1	1	3.70	21	14	51.85



(a) (b)

Figure 2: Design optimization for exterior cladding. (a) Original design with 12 types of formwork and (b) optimized design with 8 types of formwork.

design to 8 through design optimization. This allowed manufacture and construction to be completed within the project period.

4.3.4. Material Success Criterion. Positive benefits in terms of material improvement from applying digital fabrication were seen in 16 instances in 13 (48%) projects; negative benefits were not observed. Unlike conventional regular-shaped buildings constructed with traditional materials, latest materials such as UHPC, ETFE, and GRCP were applied to irregular-shaped buildings with digital fabrication, which allowed various and complex exterior envelopes. The members for irregular-shaped buildings were produced using manufacturing equipment such as a CNC machine, MDSF, MSV, and pressure using 2D manufacturing blueprints obtained through 3D models. This helps overcome the limitations of conventional construction materials. Moreover, AL. panels or copper panels that have been constantly used in the construction industry can be manufactured into three-dimensional panels depending on the design using manufacturing equipment such as press brake punches and dies tools. The irregular-shaped formwork was manufactured at a factory using a CNC machine for exposed concrete or concrete panel materials for complex shapes, and then, members were produced by placing and curing the material. In irregular-shaped buildings, the positive benefits related to quality, software issues, and integration from applying digital fabrication is inevitably associated with new material, new design, and production method.

4.3.5. Risk Success Criterion. Positive benefits in terms of negative risk reduction from applying digital fabrication were seen in 7 instances in 5 (19%) projects; negative benefits were seen in 3 instances in 3 (11%) projects. Applying digital fabrication allows reducing risk that can arise during design, manufacture, and construction stages using 3D models to generate simulations and mock-ups. However, since irregular-shaped buildings are not considered as standard construction projects, discrepancies between initial plans and execution are inevitable, which becomes a potential risk. Currently, performance data or analysis data on the case studies of irregular-shaped buildings are not readily available, which makes it difficult to proactively avoid potential risks compared to typical construction projects [11]. Nonetheless, there were more instances of expressing positive benefits in terms of risk reduction from applying digital fabrication to irregular-shaped buildings.

4.3.6. Time Success Criterion. Positive benefits in terms of time reduction or control from applying digital fabrication were seen in 7 instances in 7 (26%) projects; negative benefits were seen in 6 instances in 5 (19%) projects. Applying digital fabrication not only requires managing on-site construction but also additional off-site construction (e.g., fabrication factory). Moreover, managing new manufacturers introduced to the project because of the new manufacturing methods and consequential new supply chains becomes necessary. Such occurrences in the studied projects were either dealt with by going through trial and error in the early stages of a project before slowly learning to manage this as the project progressed or showed benefits that depended on management skills obtained from experience and skills gained throughout the project. When such management skills are put to use, great benefits, incomparable to that from the conventional production method can be achieved in the time reduction or control aspects. If not, a great amount of time may be consumed.

4.3.7. Human Resource Success Criterion. Positive benefits in terms of organization improvement from applying digital fabrication were seen in 5 instances in 4 (15%) projects. Negative benefits were seen in 1 instance in 1 (3%) project. The application of digital fabrication is very similar to the concept of lean construction. New labor, material or resources, and equipment can be allocated in the right location with JIT (just-in-time) and increase productivity. Construction involving digital fabrication requires prefabrication in a factory and transporting to a site before installation takes place. This process is different from that of a conventional construction production method, which may result in negative benefits in terms of improving and integrating processes due to inexperience in digital fabrication.

4.3.8. Scope Success Criterion. Positive benefits in terms of scope clarification from applying digital fabrication were seen in 4 instances in 4 (15%) projects; negative benefits were not observed. Digital fabrication requires defining the segments of the building, in which this production method is being applied to beforehand. Furthermore, the scope of work for design, manufacture, and construction firms responsible for digital fabrication and the scope of work and allocated tasks between initial production firms and new suppliers must be clearly defined.

4.3.9. Communication Success Criterion. Positive benefits in terms of communication improvement from applying digital fabrication were seen in 3 instances in 3 (11%) projects; negative benefits were not observed. Design, manufacture, and construction processes were established based on 3D models for irregular-shaped segments that required digital fabrication. Moreover, construction project participants carried out communication, collaboration, and arbitration using 3D models, which increased the accuracy of the design. The positive benefits from obtaining tens of thousands 2D manufacturing blueprints from 3D models were already dealt above with software issues, which seemed to have caused the low number of instances of positive benefits for communication improvement. All blueprints produced during a construction project serve as the most primary method of communication. Therefore, the study results cannot solely stand as a premise for digital fabrication with meager positive benefits for communication improvement.

4.3.10. Cost Success Criterion. Positive benefits in terms of cost reduction or control from applying digital fabrication were seen in 1 instance in 1 (4%) project; however, negative benefits were expressed in 21 instances in 14 (52%) projects. This was due to the burden of additional costs inevitably encountered when new technology is introduced in a construction project. New labor, software, and equipment are certainly required when digital fabrication is applied. Using the conventional construction method for irregular-shaped buildings can result in simultaneous loss in time, cost, and quality, which are important qualities in construction project management. On the contrary, construction project management that considers positive benefits of using digital fabrication not only allows attaining a certain quality for irregular-shaped segments but also allows reduction in time and cost.

5. Discussion

This study collected secondary data from the AIA BIM TAP Awards, the Korean BIM journals, and the Korean BIM award, various publications from conferences, websites of corresponding projects, reports, and data from actual project progress reports from professional construction firms. However, challenges persisted in discovering in-depth data for every project, and it was difficult to compile secondary data owing to discrepancies in the amount and quality of data attainable for each project. Further, while it was relatively easy to obtain data on generally well-known irregular-shaped buildings and projects that had now been completed for years, it was impossible to obtain these data for the latest irregular-shaped buildings. Nonetheless, professional construction firms with direct experience in implementing digital fabrication were sought out to supplement the incomplete data in order to improve the quality of secondary data.

In order to evaluate the benefits of applying digital fabrication for construction projects, the knowledge areas of the PMBOK were used. The success criteria on procurement management and stakeholder management were omitted because they were difficult to evaluate using the collected secondary data. It was difficult to find such terms in the secondary data because digital fabrication was still not universally implemented in the construction industry. Instead, software issues and material improvement were added as criteria to evaluate the benefits of digital fabrication for construction project management.

Content analysis was performed to investigate the degree of satisfaction for the success criteria of each project. With this approach, it is possible to see which success criterion appears more times as a positive factor and which ones appear as challenges or problems. In the previous research, Bryde analyzed the impact of BIM on construction projects through the similar research method, while this study

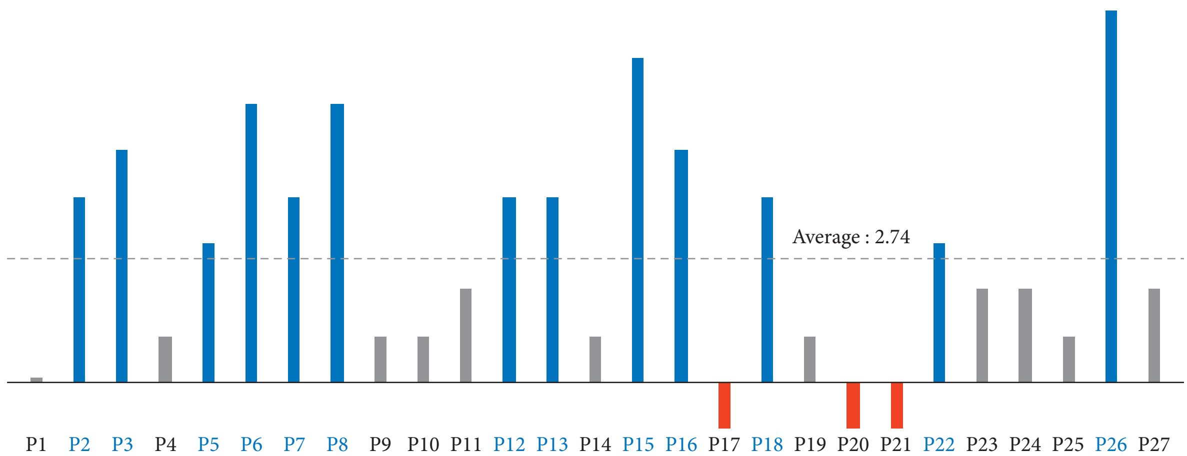


Figure 3: Scores on positive and negative benefits of using digital fabrication.

analyzed the impact of digital fabrication on construction projects. BIM supports construction as a virtual model and process, but digital fabrication is directly linked to the design, fabrication, and construction of the irregular-shaped buildings. Therefore, the analyzed results are more reliable. Among the positive benefits of digital fabrication on construction project management, quality increase and control appeared in the highest number of projects (17 out of 27 projects) at the highest frequency (26 instances). However, among the negative benefits that were mentioned as challenging or causing difficulties of digital fabrication on construction project management, cost reduction and control appeared in the highest number of projects (14 out of 27 projects) at the highest frequency (21 instances). But it does not mean that the use of digital fabrication was overall negative.

6. Conclusion

The purpose of evaluation in this study was not to find the project that used digital fabrication in the most effective way, but to find success criteria that should be considered and managed relatively more when managing projects wherein digital fabrication is applied to irregular-shaped buildings. The average score for 27 projects in the score column in Table 3 was 2.740. As shown in Figure 3, there are 13 projects with a higher score than the average.

Among these, interviews with professionals revealed that compared to other projects, projects P15 (Louis Vuitton Foundation, Paris) and P26 (University of Technology, Sydney), each with a score of 7 and 8, were examples that could be referred to as the standard application of digital fabrication or quality achievement for applying digital fabrication in the future.

Production methods employed by the construction industry are not as diverse as the currently employed manufacturing methods. However, investigating various case studies on irregular-shaped buildings showed that applying digital fabrication had significant positive benefits for construction project management. The limitation of this study is that we analyzed the advantages of digital fabrication by using highly generalized PMBOK. Future research will need to develop performance indicators that reflect the characteristics of digital fabrication technology. In particular, quantitative cost factors need to be considered.

Data Availability

The data generated or analyzed during the study are available from the corresponding author by request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2018R1A2B6007333).

References

[1] UNEP, *Building Design and Construction: Forging Resource Efficiency and Sustainable Development*, Geneva, Switzerland, 2012.

[2] IPCC, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 151, IPCC, Geneva, Switzerland, IPCC, 2014.

[3] R. Agarwal, S. Chandrasekaran, and M. Sridhar, *Imagining Construction's Digital Future*, McKinsey and Company, New York, NY, USA, 2016, http://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/imagining-constructions-digital-future.

[4] D. Chen, S. Heyer, S. Ibbotson, K. Salonitis, J. G. Steingrímsson, and S. Thiede, "Direct digital manufacturing: definition, evolution, and sustainability implications," *Journal of Cleaner Production*, vol. 107, pp. 615–625, 2015.

[5] S. K. Arora, R. W. Foley, J. Youtie, P. Shapira, and A. Wiek, "Drivers of technology adoption - the case of nanomaterials in building construction," *Technological Forecasting and Social Change*, vol. 87, pp. 232–244, 2014.

[6] I. Agustí-Juan, F. Müller, N. Hack, T. Wangler, and G. Habert, "Potential benefits of digital fabrication for complex structures: environmental assessment of a robotically fabricated concrete wall," *Journal of Cleaner Production*, vol. 154, pp. 330–340, 2017.

[7] J. Pinkse and M. Dommisse, "Overcoming barriers to sustainability: an explanation of residential builders' reluctance to adopt clean technologies," *Business Strategy and the Environment*, vol. 18, pp. 515–527, 2009.

[8] X. S. Lee, C. P. Yan, and Z. S. See, "Irregular shaped building design optimization with building information modelling," *MATEC Web of Conferences*, vol. 66, Article ID 00027, 2016.

[9] M. J. See and S. Jeong, "The effects of irregular shaped buildings on the perception and preference of streetscapes," *Journal of Korea Planning Association*, vol. 47, no. 7, pp. 109–118, 2012.

[10] H.-G. Ryu, "Deduction of considerations during design and construction by analysing domestic and abroad case analysis of freeform building envelope," *Korean Journal of Construction Engineering and Management*, vol. 14, no. 4, pp. 84–96, 2013.

[11] E.-Y. Lee and Y.-S. Kim, "An analysis and improvement of free form building's construction productivity-focused on exposed concrete work-," *Korean Journal of Construction Engineering and Management*, vol. 15, pp. 38–46, 2014.

[12] B. W. Jeon, Y. O. Kim, and N. W. Lee, "Characteristic of spatial configuration in the informal structure of frank O. Gehry," *Journal of the Architectural Institute of Korea Planning & Design*, vol. 22, no. 6, pp. 39–46, 2006.

[13] J. H. Kim, "Our efforts to design complex-shaped tall building," *Review of Architecture and Building Science*, vol. 56, no. 4, pp. 20–34, 2012.

[14] H. G. Park, "Use of concrete for iconic buildings," *Review of Architecture and Building Science*, vol. 60, no. 2, pp. 34–39, 2016.

[15] E. S. Jung, S. J. Kim, N. H. Ham, S. K. Moon, and J. J. Kim, "A case study on the project benefit of digital fabrication in construction projects," *KIBIM Magazine*, vol. 8, pp. 24–34, 2018.

[16] M. Brandenburg, K. Govindan, J. Sarkis, and S. Seuring, "Quantitative models for sustainable supply chain management: developments and directions," *European Journal of Operational Research*, vol. 233, no. 2, pp. 299–312, 2014.

[17] N. Blismas, C. Pasquire, and A. Gibb, "Benefit evaluation for off-site production in construction," *Construction Management and Economics*, vol. 24, no. 2, pp. 121–130, 2006.

[18] F. H. Abanda, J. H. M. Tah, and F. K. T. Cheung, "BIM in off-site manufacturing for buildings," *Journal of Building Engineering*, vol. 14, pp. 89–102, 2017.

[19] S. Son, H. Park, and K. H. Lee, "Automated laser scanning system for reverse engineering and inspection," *International Journal of Machine Tools and Manufacture*, vol. 42, no. 8, pp. 889–897, 2002.

[20] A. M. Chu, "Integration of CAM systems into multi-axes computerized numerical control machines," in *Proceedings of the 2010 Second International Conference on Knowledge and Systems Engineering (KSE)*, pp. 119–124, Hanoi, Vietnam, October 2010.

[21] A. Guzik, *Digital Fabrication Inspired Design: Influence of Fabrication Parameters on a Design Process*, , Master's Thesis, University College London, 2009.

[22] M. Kreiger and J. M. Pearce, "Environmental life cycle analysis of distributed three-dimensional printing and conventional manufacturing of polymer products," *ACS Sustainable Chemistry & Engineering*, vol. 1, no. 12, pp. 1511–1519, 2013.

[23] J. Faludi, C. Bayley, S. Bhogal, and M. Iribarne, "Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment," *Rapid Prototyping Journal*, vol. 21, no. 1, pp. 14–33, 2015.

[24] M. Gebler, A. J. M. Schoot Uiterkamp, and C. Visser, "A global sustainability perspective on 3D printing technologies," *Energy Policy*, vol. 74, pp. 158–167, 2014.

[25] J. P. Womack, D. T. Jones, and D. Roos, *The Machine That Changed the World*, Free Press, New York, NY, USA, 2007.

[26] B. Joseph Pine, *Mass Customization: The New Frontier in Business Competition*, Harvard Business Press, Boston, MA, USA, 1993.

[27] I. Gibson, D. W. Rosen, and B. Stucker, *Additive Manufacturing Technologies-Rapid Prototyping to Direct Digital Manufacturing*, Springer, Boston, MA, USA, 2010.

[28] S. Ford and M. Despeisse, "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges," *Journal of Cleaner Production*, vol. 137, pp. 1573–1587, 2016.

[29] C. Kohtala, "Addressing sustainability in research on distributed production: an integrated literature review," *Journal of Cleaner Production*, vol. 106, pp. 654–668, 2015.

[30] N. Dunn, *Digital Fabrication in Architecture*, Laurence King Publishing Ltd., London, UK, 2012.

[31] F. Gramazio and M. Kohler, *Digital Materiality in Architecture*, Lars Müller Publishers: Baden, Zurich, Switzerland, 2008.

[32] F. Gramazio, M. Kohler, and S. Langenberg, *FABRICATE: Negotiating Design & Making*, gta Verlag, Zurich, Switzerland, 2014.

[33] K. Salonitis and P. Stavropoulos, "On the integration of the CAx systems towards sustainable production," *Procedia CIRP*, vol. 9, pp. 115–120, 2013.

[34] R. Sacks, L. Koskela, B. A. Dave, and R. Owen, "Interaction of lean and building information modeling in construction," *Journal of Construction Engineering and Management*, vol. 136, no. 9, pp. 968–980, 2010.

[35] S. Eckblad, H. Ashcraft, P. Audsley et al., *Integrated Project Delivery—A Working Definition*, AIA California Council, Sacramento, CA, USA, 2007.

[36] O. A. Olatunji, "Modelling the costs of corporate implementation of building information modelling," *Journal of Financial Management of Property and Construction*, vol. 16, no. 3, pp. 211–231, 2011.

[37] D. Bryde, M. Broquetas, and J. M. Volm, "The project benefits of building information modelling (BIM)," *International Journal of Project Management*, vol. 31, no. 7, pp. 971–980, 2013.

[38] J. R. Duflou, J. W. Sutherland, D. Dornfeld et al., "Towards energy and resource efficient manufacturing: a processes and systems approach," *CIRP Annals*, vol. 61, no. 2, pp. 587–609, 2012.

[39] Y. Umeda, S. Takata, F. Kimura et al., "Toward integrated product and process life cycle planning-An environmental perspective," *CIRP Annals*, vol. 61, no. 2, pp. 681–702, 2012.

[40] S. Ibbotson and S. Kara, "LCA case study. Part 2: environmental footprint and carbon tax of cradle-to-gate for composite and stainless steel I-beams," *International Journal of Life Cycle Assessment*, vol. 19, no. 2, pp. 272–284, 2013.

[41] S. Ibbotson, T. Dettmer, S. Kara, and C. Herrmann, "Eco-efficiency of disposable and reusable surgical instruments-a

scissors case," *International Journal of Life Cycle Assessment*, vol. 18, no. 5, pp. 1137–1148, 2013.

[42] S. Manmek, H. Kaebernick, and S. Kara, "Simplified environmental impact drivers for product life cycle," *International Journal of Sustainable Manufacturing*, vol. 2, no. 1, pp. 30–65, 2010.

[43] S. H. MoosaviRad, S. Kara, and S. Ibbotson, "Evaluating CO_2 emissions associated with international outsourcing in manufacturing supply chains," *Modern Applied Science*, vol. 7, no. 10, pp. 20–33, 2013.

[44] W. Li, M. Winter, S. Kara, and C. Herrmann, "Eco-efficiency of manufacturing processes: a grinding case," *CIRP Annals*, vol. 61, no. 1, pp. 59–62, 2012.

[45] S. Thiede, *Energy Efficiency in Manufacturing Systems*, Springer, Berlin, Germany, 2012.

[46] E. Kunnari, J. Valkama, M. Keskinen, and P. Mansikkamäki, "Environmental evaluation of new technology: printed electronics case study," *Journal of Cleaner Production*, vol. 17, no. 9, pp. 791–799, 2009.

[47] W. R. Morrow, H. Qi, I. Kim, J. Mazumder, and S. J. Skerlos, "Environmental aspects of laser-based and conventional tool and die manufacturing," *Journal of Cleaner Production*, vol. 15, no. 10, pp. 932–943, 2007.

[48] S. Vinodh, "Improvement of agility and sustainability: a case study in an Indian rotary switches manufacturing organisation," *Journal of Cleaner Production*, vol. 18, no. 10-11, pp. 1015–1020, 2010.

[49] R. Sebastian, "Changing roles of the clients, architects and contractors through BIM," *Engineering, Construction and Architectural Management*, vol. 18, no. 2, pp. 176–187, 2011.

[50] G. Aranda-Mena, J. Crawford, A. Chevez, and T. Froese, "Building information modelling demystified: does it make business sense to adopt BIM?," *International Journal of Managing Projects in Business*, vol. 2, pp. 419–434, 2009.

[51] F. Lindner and A. Wald, "Success factors of knowledge management in temporary organizations," *International Journal of Project Management*, vol. 29, no. 7, pp. 877–888, 2011.

[52] H. Harris, "Content analysis of secondary data: a study of courage in managerial decision making," *Journal of Business Ethics*, vol. 34, no. 3-4, pp. 191–208, 2001.

[53] AIA, *AIA TAP BIM Awards*, 2017, http://www.aia.org/aia-architects.

[54] S. H. Koh, N. H. Ham, J. S. Lee, S. W. Yoon, and J. J. Kim, "Comparison analysis of BIM level in the domestic and overseas BIM projects - focused on BIM jornal and award winning projects," *KIBIM Magazine*, vol. 7, pp. 25–35, 2017.

[55] A. J. Shenhar, D. Dvir, O. Levy, and A. C. Maltz, "Project success: a multidimensional strategic concept," *Long Range Planning*, vol. 34, no. 6, pp. 699–725, 2001.

[56] Project Management Institute, Inc., *A Guide to the Project Management Body of Knowledge (PMBOK Guide)*, Project Management Institute, 5th edition, 2013.

[57] AIA, *Building Information Evolved, Foundation Louis Vuitton, AIA TAP BIM Awards 2012*, 2012.

[58] NMoQ National Museum of Qatar, *WSI Design and Engineering Methodology*, 2012.

[59] NMoQ National Museum of Qatar, *WSI Design Optimization SSS, Panels, Embeds*, 2013.

[60] NMoQ National Museum of Qatar, *Work Method Statement Fabrication of Ultra High Performance Fiber Reinforced Concrete Panels for National Museum of Qatar*, 2012.

[61] NMoQ National Museum of Qatar, *Methodology of Survey works of FRC Secondary Steel Structure for National Museum of Qatar*, 2012.

[62] N. H. Ham, B. J. Ahn, and J. J. Kim, "Specialty contractor's role and performance analysis for digital fabrication-focusing on the case of irregular podium construction," *KIBIM Magazine*, vol. 8, pp. 43–55, 2018.

[63] CATIA 3DEXPERIENCE-on-the-Cloud Brings High Power Design Tools to Small Design Teams, 2015.

[64] Withworks, "Irregular cladding panel fabrication for KEB Hana Bank in Samsung-dong," *Architectural Façade Magazine 'Exterior'*, vol. 214, pp. 44–49, 2017.

Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 9872736, 15 pages
https://doi.org/10.1155/2019/9872736

Research Article

Development of a Web Application for Historical Building Management through BIM Technology

F. Rodrigues,[1] J. Teixeira,[1] R. Matos,[1] and H. Rodrigues [2]

[1]*RISCO, University of Aveiro, Aveiro, Portugal*
[2]*RISCO, School of Technology and Management, Polytechnic Institute of Leiria, Portugal*

Correspondence should be addressed to H. Rodrigues; hugo.f.rodrigues@ipleiria.pt

Received 14 October 2018; Accepted 13 December 2018; Published 17 January 2019

Academic Editor: Edmundas K. Zavadskas

Nowadays the built heritage has been recognized as one of the main sectors that can support the economic and sustainable development of countries. In the last years, the built heritage has been subject to several levels of interventions, being now clear its need for a proper maintenance and conservation management. However, in several cases, the maintenance faces lack of building records, which makes the maintenance a harsh, long, and expensive process. Therefore, there is an opportunity and need to apply new technologies, like Building Information Modelling (BIM), as supporting tool to the management of historical heritage. By so, the aim of this work was the development of a management system to be used as a supporting tool to the maintenance and conservation of the existent buildings, in historical context, facilitating to the interested parties the automated and digitized information needed to carry out the most varied tasks, with the particularity to be directly connected to the 3D-BIM model of the building. But in order to test the developed system (its applicability and functionality), it was in an early phase, applied to a pilot project with the significant heritage value. This work follows a development methodology applied to the case study and had different phases: (1) the case study was modelled in Autodesk Revit software, in whose model was inserted all the parametric information and associated metadata; (2) then, a support database of the management system was developed in Microsoft SQL Server, which will support all the information exported from the BIM model; (3) a web application was developed in C# through Visual Studio 2015, which works through and application programming interface (API) allowing the communication between the web application and the BIM model, allowing not only the interaction with the parametric information of this one, but also, a persistent access to a data management system (drawings, inspection reports, specifications, etc.) that has been created. The development of the management system and its application to the case study allows us to show its potential as a tool for the historical heritage management, contributing to its permanent and constantly updated management and cross off the fragmentation and loss of information therefore reducing the consequent investment in data collection.

1. Introduction

During last years, the historical and cultural heritage has been classified as a strategic sector for the development of economic, sustainable, and more cohesive society [1]. Countries have been concerning about the preservation of the historic assets, existing currently a special concern urban centres, which are the main holders of the historic heritage. However, the biggest concern related with refurbishment and maintenance interventions is the lack of data and information about existent buildings. The management and maintenance of buildings is a complex task and an onerous process.

Maintenance theory currently exists but fails when applied in practical application and implementation [2]. Thus, a study of heritage buildings management processes is essential.

Therefore, the main objective of this work is to propose a tool to integrate heritage buildings management within digital technologies, namely, Building Information Modelling (BIM).

The introduction of new digital technologies in the field of heritage is an opportunity to create three-dimensional models as effective communication tools, sharing and visualising interfaces either to physical and structural features, as for its historic inventory [3].

Depending on technology used, it is also possible to obtain other types of information, such as, historical data, conservation state, materials, and constructive techniques used [3]. Thus, it is recognized that BIM is a multidisciplinary technology and it is essential to building lifecycle management, such as, maintenance and development of the growing inventory of heritage [4].

BIM methodology has other applications and can be used as a database, to support project teams and to integrate as-built information in order to plan monitoring and maintenance of buildings during its lifecycle [5]. This information is supported by periodic visual inspections and monitoring equipment that are essential to preserve the historic heritage [3].

In this work, a methodology was developed and to be validated was applied to a case study.

The methodology adopted to be applied to the case study follows the following steps:

(1) Data analysis: architecture and structure projects, historic information throughout documentation analyses, and technical information by tests and visual inspections
(2) The object of study modelling in accordance with the BIM methodology with recourse to Revit Autodesk software
(3) Development of databases for the object of study inventory
(4) Development of a management model in Visual Studio 2015 with recourse to an API developed in C#
(5) Implementation of the management model inside of a web application
(6) Results analysis

Therefore, in the next chapters, some important concepts are approached to understand the methodology applied, and those are presented and validated by applying them to a case study. Finally, the results are analysed.

2. Review

2.1. Heritage Documentation. Heritage documentation management encourages the use of computerized techniques to preserve the information produced [6]. The quantity of data produced during the working on a site can quickly become huge. The worldwide scientific work on the metadata concept is expanding rapidly. In heritage data recording, forums and institutions appeared, such as The Forum on Information Standards in Heritage (FISH) and the English Heritage Data Standards Units (DSU). This one works for the development of standards for heritage data.

There are also some approaches in web applications for management of cultural heritage, such as a web information system for the management and dissemination of cultural heritage data applied to archaeologist developed by Meyer et al. [6]. A web-based application for interactive users' access and exploration of three-dimensional models providing integrated geometrical and nongeometrical information by an intuitive interface is developed for cultural heritage sites and artefacts by Guarneri et al. [7].

there are some applications of 3D modelling to support cultural heritage management, namely, 3D models that include digital documentation of monuments and sites studied by Styliadis [8]; Pavlidis et al. [9]; Yilmaz et al. [10]; Haggrén et al. [11]; and Grussenmeyer and Jasmine [12].

Bassier et al. [13] compared the complex geometric models, considering the data acquisition, the modelling, and the structural analysis of timber roof structures defined in a Building Information Modelling to a traditional wire-frame model, and showed that the BIM complex models provide a more reliable result in terms of geometry and structural behaviour.

Portier et al. [14] presented a computerized methodology as an assistance tool for archaeological hypotheses. They present a study for storage and consultation of archaeological archives, for the communication functionality, for the exchange of information and creation of a virtual museum for ancient part of historic city. However, the software used was very expensive.

Lopez et al. [15] recognized that the current approaches show that BIM tools and GIS tools supported by auxiliary software are an effective solution for managing and modelling graphical and semantic data, in a semiautomatic way, and this is only possible once the common data structure IFC allows the interoperability of information and communication between the different actors that are involved in architectural heritage rehabilitation, reconstruction, or maintenance processes.

Thus, this paper has some contributions for this area. It aims at presenting a methodology supported by BIM in order to achieve the three-dimensional model, and then through an API, it is possible to connect parametric data between BIM and database (in a bidirectional flow). The 3D model, parametric data, and digitalized information of the project can be depicted and consulted in a web application. Once, in Portugal, there is a delay in the BIM methodology application; the methodology presented in this paper is considered innovative and important to support technicians and heritage managers.

2.2. Building Information Modelling: BIM. Currently, the use of BIM methodology has been performing a highlight role in the process of architecture, engineering, construction and operation (AECO).

Projects development throughout BIM has become a demand in several countries. Development, study, simulation, and assessment of projects by BIM methodology transformed the current processes of conception, communication and information necessary to do, and delivering a project, in order to posterior construction and management of the building (Lopez, 2016).

Building Information Modelling is an advanced paradigm of collaborative work, based on interactive models applied over information models, regularly updated and synchronized. A set of processes and technologies that interact between them compose BIM. Thus, this methodology enables to manage the project and its data over its lifecycle [16].

Therefore, this methodology is applicable to historic heritage management, as far as allows registering, studying, modifying, and updating and keeping the object for future generations. In addition, it contains other features, such as three-dimensional visualisation, animations, and automatic production of documents (plans, elevations, sections, construction details, reports, schedules, etc.) [17].

One of the main advantages and applications of BIM methodology is to be able to integrate parametric objects into a 3D model allowing its direct interaction and communication with all the other components, granting a fully parametric model, which precisely permits the functionalities that must be applied and explored in heritage [18].

In order to have a better understanding about BIM, it is necessary to know about its foundations basis which are the modelling oriented by objects and interoperability [19].

Modelling oriented by objects is related to parametric objects (objects such as windows, doors, walls, roofs, and all the elements categorized as part of a project) which are defined as an integrated part of the system, which takes into account the relation and interaction between other objects [17].

Interoperability consists on the ability to communicate between the different systems throughout the different phases of the constructive process, granting an automated modelling and design process to the interested parties without loss of time or information.

Modelling oriented by objects and an efficient and interoperability flow allows us to take advantage of information to create BIM workflows that are more efficient than the traditional processes based in CAD [19, 20].

Besides this, due to multidisciplinary of the BIM process, to different level complexity of data and to high quantity of tools available to analyse this set of information of each domain, the possibility of information sharing between different software's through Industry Foundation Classes (IFC) format arises. IFC is a format of data archive directed for the object, which allows us to share information between different software. It represents a nonpropriety format being an open source with a common language used for sharing information between models of different developers [21]. It is relevant to highlight that allows integrate XML language enabling the circulation of information. Thus, this is towards other processes than projects.

BIM methodology has specifications, standards, and guidelines established in some countries, which already adopted BIM in their processes [22]. The National Building Information Modelling Standard [23] was developed in the United States of America; the National Common BIM Requirements (COBIM) was developed in Finland; and in the United Kingdom, there is PAS 1192-2: Specification for Information Management using BIM [22]. The requests of BIM implementation allied to current globalisation processes of the construction sector and boost companies to use this methodology in order to increase international competitiveness.

In Portugal, application of BIM is delayed due to several factors, such as lack of need to implement BIM technology; lack of experience in BIM; conventional practice in 2D and 3D; and steep process to acquisition of knowledge in BIM [24]. Besides this, standardisation in Portugal is in the beginning. However, Portuguese Institute of Quality (responsible for the Portuguese standardisation process) is represented in the work group of European Commission for normalisation in order to develop the European BIM standard [25].

In the BIM domain, it is necessary to attribute the definition of strategies and procedures to assets data for the respective model, namely, parameters and information to be attached and integrated in the model. So, when the information and parameters are integrated in the model, this means that there exists an external database associated with BIM model with a bidirectional relation. For example, this database can be Access SQL, Open Database Connectivity (ODBC), or Construction Operations Building Information Exchange (COBie). To be able to manage all the information integrated in the model, it becomes clear the need to ensure the elements classification to all the interested parties, so they are able to work with categorized elements. There are currently several classification systems in place, but the most used are the Uniclass, Master Format, and OmniClass. These classification systems grant every element, building, activity, job, or timeline a code for universal understanding, granting better workflow between different parties.

Besides this, BIM provides ways to manage the building lifecycle through the integration of information in the model. However, the tools to create and manage that same information for existent building projects are being developed in BIM [26].

One of the main concerns of the implementation of the information management based on a BIM model is related to the historical building's records and data, which are almost the times incomplete or obsolete [27]. Thus, the management of historical building was completely ineffective till few years, and it has not been even a reliable methodology to implement it. However, BIM can be applied to heritage since it can digitalize and able to model all the historical and constructive information from the existent buildings. However, there are BIM libraries with objects and families for new construction, and there is a lack of information related to existent and historical buildings. Thus, the need of this development and these difficulties result in the Historical Building Information Modelling (HBIM) to give answer for the complex modelling process of historical buildings' objects.

2.3. HBIM. HBIM is a recognized tool that works like a plug-in for BIM, defined as a system of model of historical structures. These tools work with data obtained from laser scanning and photogrammetry [10, 28–32]. Thus, with these processes, it is possible to speed up the building model and the opportunity of developing object libraries. Besides this, it supports the comprehension of the objects [10]. As recognized by Baik [33], one of the most important parts of HBIM is transferring the information that is based on the rich data survey into 3D parametric modelling. The model provided by the context to data of different types is no longer the final phase of heterogeneous information synthesis, but it is becoming a working tool that recognizes the construction of geometric and technological manufacturing models as valid support for the monitoring of degradation and of structural behaviour [34].

Figure 1 describes the methodology proposed for HBIM application in historical buildings. This process involves (1) collecting and processing the data from laser scanning/photogrammetry; (2) identification of historical details based on architecture books; (3) construction of historical parametric components/objects; (4) mapping of parametric objects in the project; and (5) production of final projects.

Thus, through HBIM, it is possible to produce automatically complete projects of engineering for building conservation, which includes three-dimensional models, schedules, details, plans, and sections [29].

Besides these features, BIM can add to the project and to the objects other information through shared parameters and project parameters. These parameters are editable, and there are different types since text, numbers, date, dimensions, etc. Therefore, it is possible to complement the project with other data not normalised in the software, turning the application of this tool very significative, being very important the application of these parameters in BIM for historical building [35]. By using these tools, it is possible to combine information that would otherwise be very hard to combine [36].

So, there is an arise of the need to explore the integration of the information from these parameters, in an interactive and intercooperative management model, in order to integrate all the information and data generated by BIM in a management platform. Due to this need, this work aims at the development of a management system to be used as a supporting tool to the maintenance and conservation of the existent heritage buildings. This tool will facilitate the interested parties the automated and digitalized information needed to carry out the most varied tasks, with the particularity to be directly connected with the 3D-BIM model of the building. In order to test the developed system (its applicability and functionality), it was applied to a building with the significant heritage value known as Casa de Santo António located in Ílhavo, Aveiro, in the centre of mainland Portugal. Then, a support database of the management system was developed in Microsoft SQL Server®, which will support all information exported from the BIM model. A web application of heritage building management was also developed through BIM since this methodology is enabled in the domain of data management and data communication. In the BIM project, the main requirements are to ensure the information exchange, and the integrated extraction of documents that when allied to a collaborative methodology of workflow, can increase the integration of every intervenient [37].

In the last year, several research projects in the domain of data collecting and management and HBIM development have been developed or are undergoing in the framework of FP7 and currently progressing EU Horizon 2020 projects, reflecting the high relevance for understanding and support of management of cultural heritage assets. Among the several examples, the INCEPTION project is related to the innovation in 3D modelling of cultural heritage through an inclusive approach for time-dynamic 3D reconstruction of artefacts, built and social environments, and addresses several topics such as the moisture detection in heritage buildings by 3D laser scanning [38], semiautomatic generation of BIM models for cultural heritage [39], and procedures to integrated data capturing requirements for 3D semantic modelling of cultural heritage [40], among others. The HeritageCARE project is part of the Interreg-SUDOE program that aims at the monitoring and preventive conservation of historical and cultural heritage implementing a system for the monitoring and preventive conservation of heritage with historical and cultural values in South-West Europe [41]. BIM4REN is a project devoted to aBIM tools for all the building renovation value chain. The project identified that the innovation in this field can be of major importance to reduce costs, develop smarter solutions, and streamline processes, namely, by the collection of data for the characterization of the existing buildings, management, and consolidation of the data and data driven design for optimal selection.

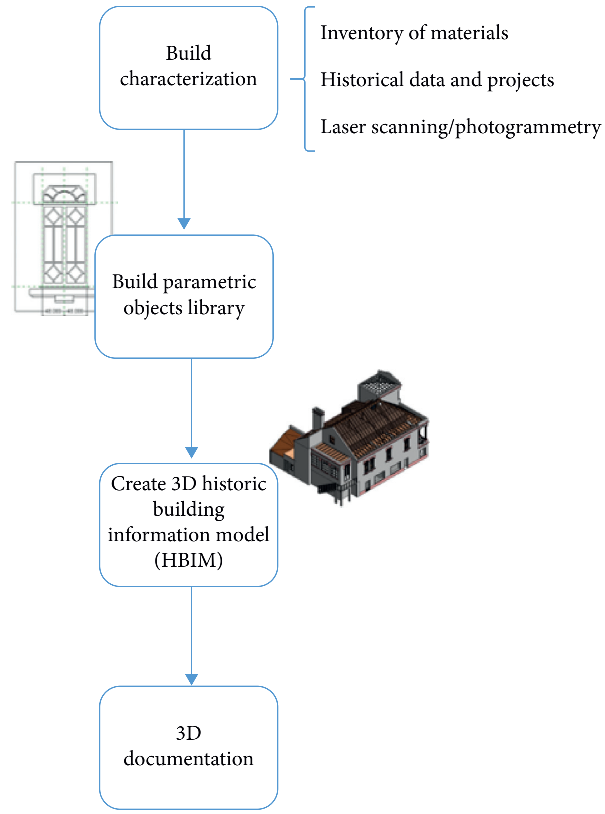


Figure 1: Historical building information modelling flowchart.

3. Methodology

3.1. Introduction. According to Baik and Boehm [42], there is a high necessity of the development of an integrate management methodology for historical buildings, in order to grant its preservation and maintenance and allow the decision-makers about which buildings need interventions, maintenance, and demolition actions. So, the development and integration of the data system within a BIM model and how that same data system can be connected between the BIM Model and the user is presented. Figure 2 depicts the scheme proposed and developed, representing the interconnection between the BIM model, a data system, and a web management platform.

This system is based on an organizational and functional structure, in order to keep sustainability and automation of the historical heritage management. Thus, the system can be divided into two substructures: the core and the user interface.

3.2. Development. The first part core is the system architecture, and inside it, it includes the BIM model, the database system, and the API.

The first step was to develop a full parametric building model in software Revit.

Then, it was studied the Database Link (DBLink) since BIM methodology has the ability to export and import data through the DBLink plug-in. This plug-in was developed by Autodesk, and it aims at exporting and importing data from Revit for an external database, which can be done to Excel, Access, MSSQL, MySQL, Oracle, MongoDB, Redis, or other database management software. The practical application of this plug-in was studied, by connecting the BIM model and the management system. This allowed us to export and import information from one model to another.

The next step was to create a support database to the management system that would serve as a bridge to interconnect the database from the BIM model and the management system. A database is a tool to collect, store, and organize data, like a repository of information related to an issue. Thus, the database management system is software that manages the storage and manipulation and searches the existing information in the database. In this case, the database management system is based on relational characteristics. It was developed using Microsoft SQL Server (MSSQL), and it aims at supporting all the information exported from the BIM model. Thus, the information from the BIM model goes to the database, and it is organized by 3 phases and 5 categories, as it is represented in Figure 3.

It is essential to create credentials to restrain the user access that can be Administrator (access without constraints), Read (access limited only for read material), or ReadWrite (access to read and write but with constraints). Each user has an Id, e-mail/username, and password. Thus, the user can access their list of projects.

Project information includes 5 categories: drawings from Revit or other type of drawings that user wants to add as complement to the project; facility management information and data which allow us to access the external database of BIM model and read or edit the information about any family of objects (edition of data just included in shared parameters); documentation, which allows information storage such as historic contextualization, intervention information, and photographic collection; reports, which allow the storage of data related to information about the conservation status and include inspection reports, structural analysis, tests and inspection reports, etc.; BIM models that allow us to view any kind of graphic information about any element allowing to update the model when the building is submitted to interventions and/or maintenance actions.

Figure 4 allows a better understanding about the organisation of the management model, where it is possible to see the application of the methodology.

After, a web application (http://www.gestheritage.web.ua.pt) was developed in C# using Visual Studio 2015 software. It works through an Application Programming Interface (API) that allows the communication between the web application and the BIM model, allowing not only the interaction with the parametric information of this one, but also, a persistent access to the data system (drawings, inspection reports, specifications, etc.) previously created. The development of the Web API was done due to the need to facilitate the user to access project information.

Web application was developed, named as "Gestheritage," and was implemented in the hosting service of the University of Aveiro. Finally, the second substructure of the development management system was the user interface, which represents the way that the user interacts with the application. The web application is presented in Figures 5–7.

Thus, the user can communicate with the web application, this one communicates with the API, and the API communicates with the database. The process is represented in Figure 8.

4. Case Study

4.1. Description. The case study is related to a residential house named "Casa de Santo António," located in the centre city of Ílhavo, Aveiro, Portugal. This house is considered one of the most iconic local buildings with great patrimonial value (Figures 8 and 9)

This building was built in 30s of the twentieth century, with the category of residential house. Nowadays, it is the head office of InovaDomus Association. The University of Aveiro and more than 10 companies linked to the construction sector are working in this building, in the scope of the ReabilitaDomus project, since 2012 [43].

This building was classified as a building of excellent architecture, and it is composed by 2 stories and an attic, with a total area of 450 m^2.

The structural materials are composed of masonry, wood, and concrete. Masonry brick composes essentially the structural walls with variable thickness, anchored by continuous foundations of poor concrete and adobe. The ground floor has a regularization screed of 2 cm. The first floor is composed by wooden beams distant of 0.6 m, with a locking system for buckling, constituted by dowel perpendicular to wooden beams. There are some concrete reinforcements (beams and columns) included in the building [43, 44].

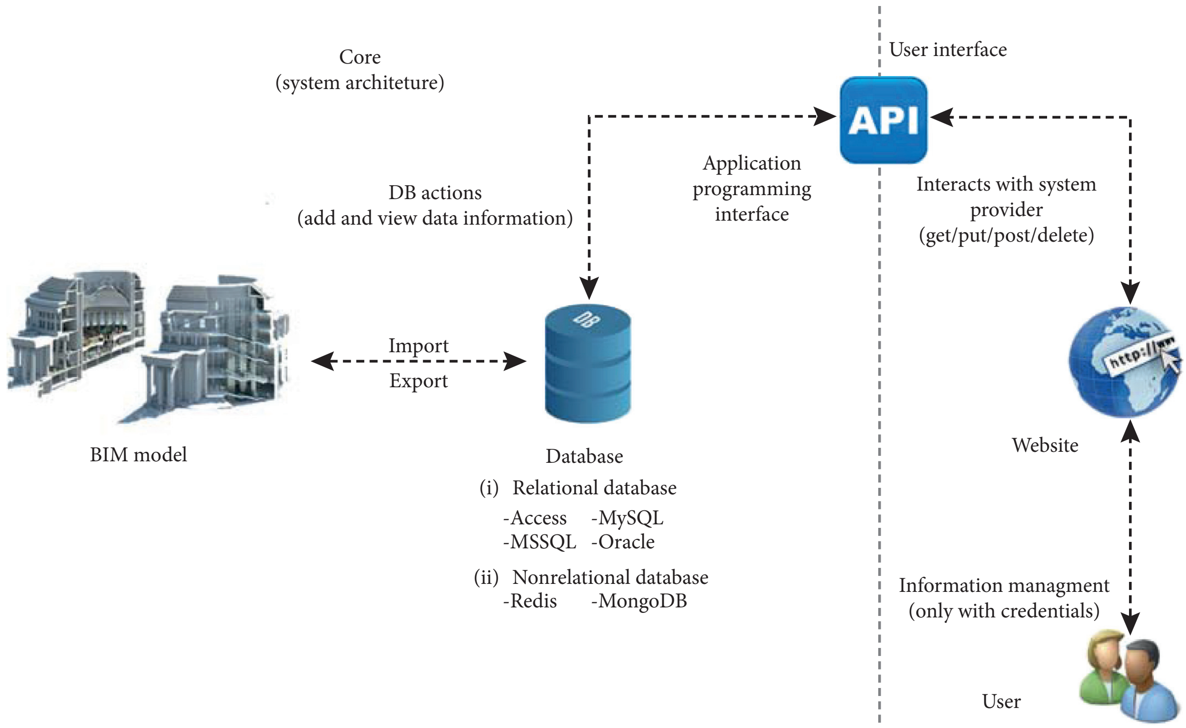


Figure 2: Scheme of the development of the management of the historical heritage model proposed.

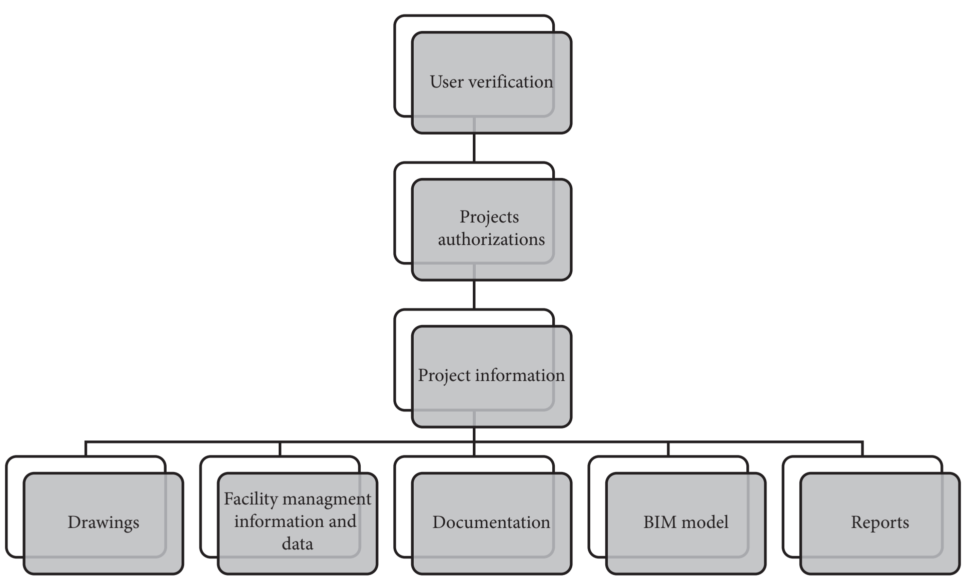


Figure 3: Organisation chart of the historical heritage management model structure.

The first part of the application of this methodology started with the case study modelling in BIM, through Revit Autodesk being the architecture and structural components of the building modelling.

4.2. Modelling. The characterization of all components included in the building (construction materials, geometry, and structural behaviour) was done. This survey was carried out in situ and throughout documentation analyses, such as reports of structural characterization [44]. Thus, it was possible to do the characterization of the building and develop the BIM model of the building.

4.2.1. Architecture and Structure. Although the building was a particular case with a great architectural detail, it was not possible to model through the point cloud, and by so, the modelling work was highly time-consuming. Adequate objects and families closer to the existent components of the building were developed.

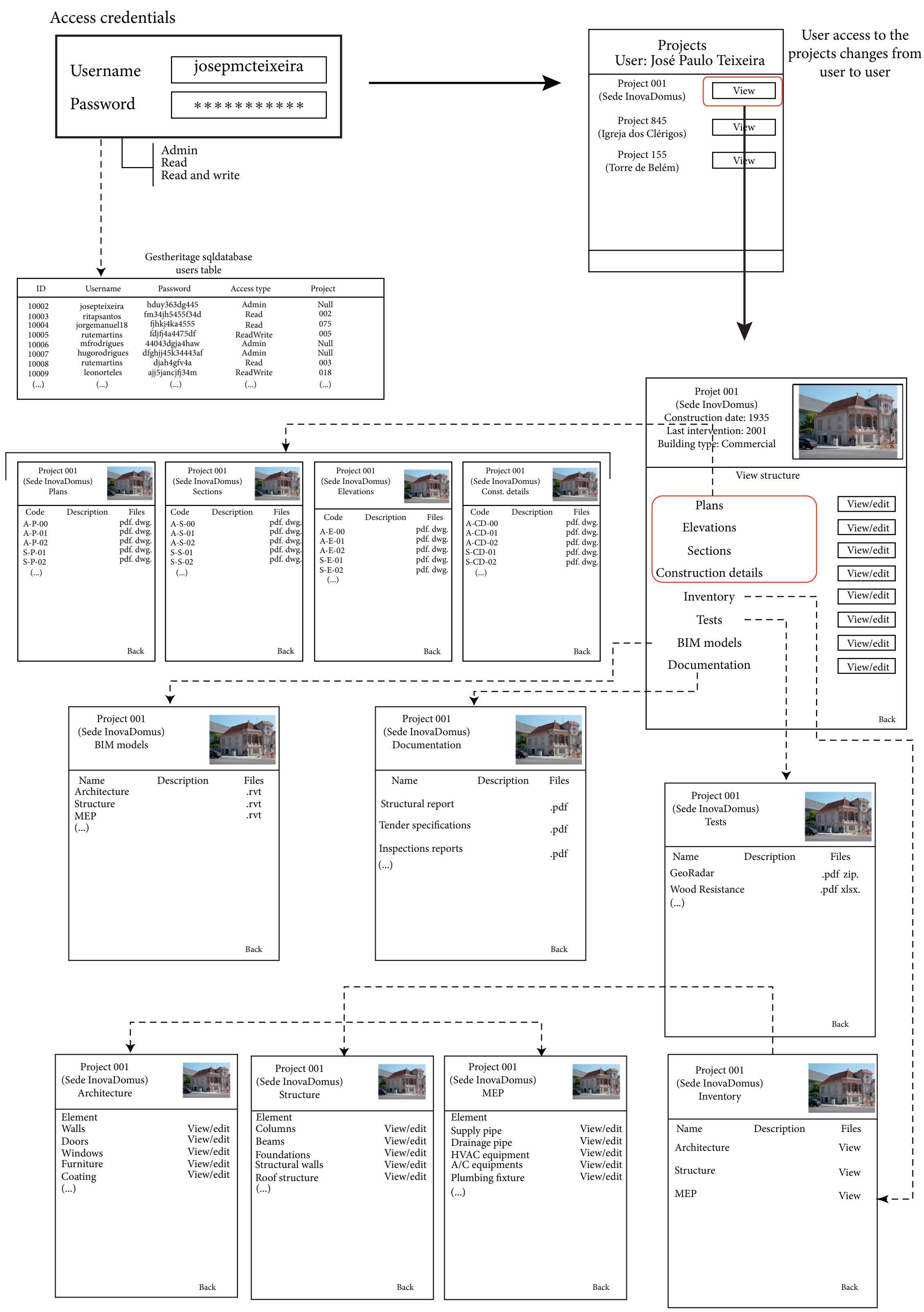


Figure 4: Organizational structure of the management model.

In Figure 10, the real building and the BIM model developed and the respective elevations are presented.

In Figures 11 and 12, other views of the building BIM model are represented. InovaDomus provided structural plans, which were used to develop structural components in the BIM model.

This BIM model was used as a plug-in of the Autodesk library—Classification Manager, in order to associate the

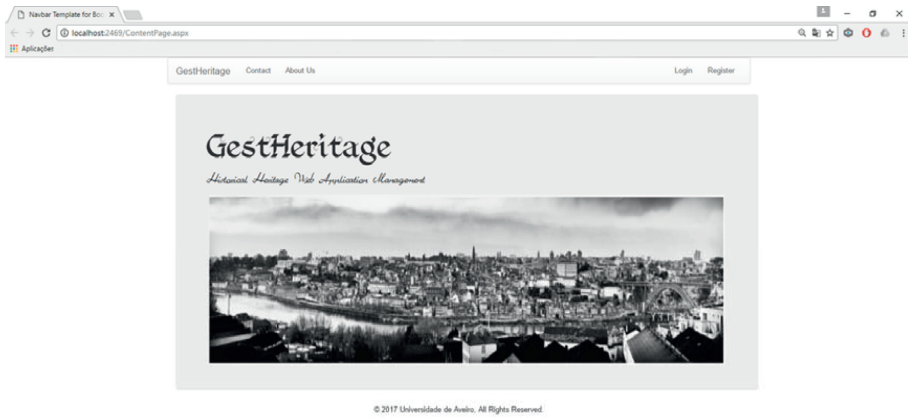


Figure 5: GestHeritage index page.

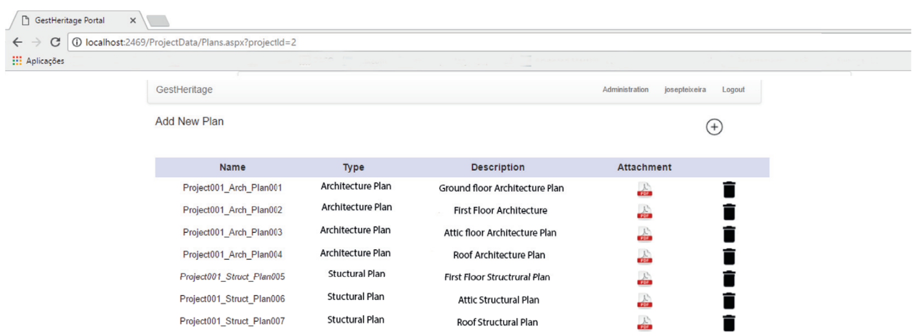


Figure 6: GestHeritage Plans page.

Figure 7: Relational scheme between user, web application, API, and SQL database.

Figure 8: Current state of the building: left and main facades.

Figure 9: Current state of building: main facade.

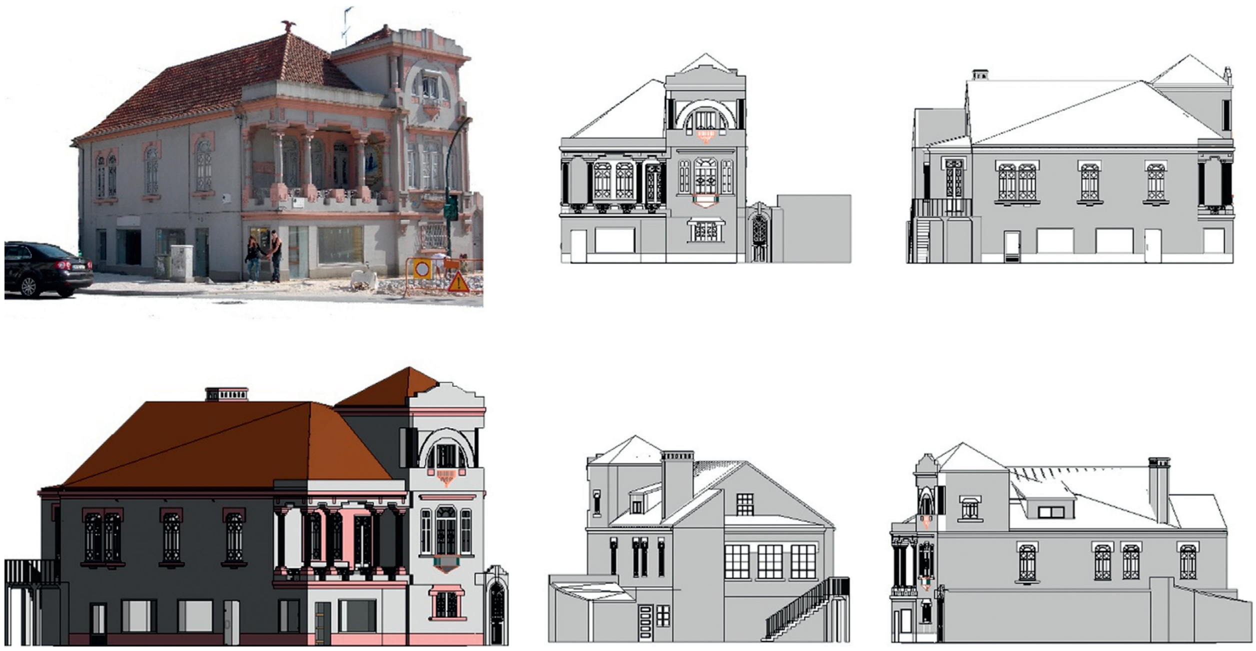


Figure 10: Current Building vs 3D Model: Santo Antonio House and Elevations in *Autodesk Revit.*

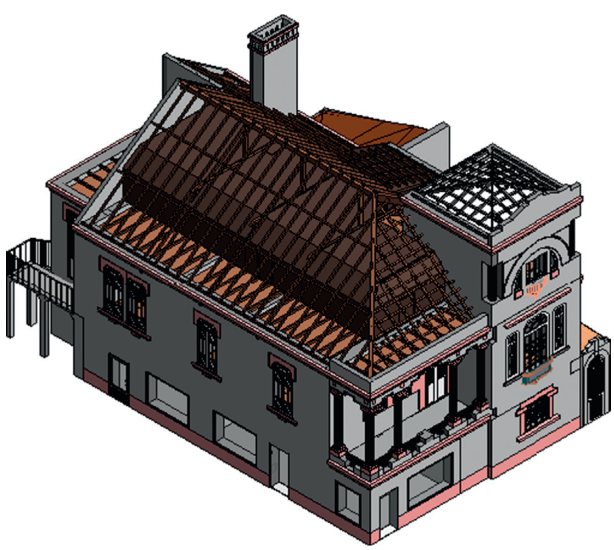


Figure 11: 3D view of the BIM model (main and left elevation).

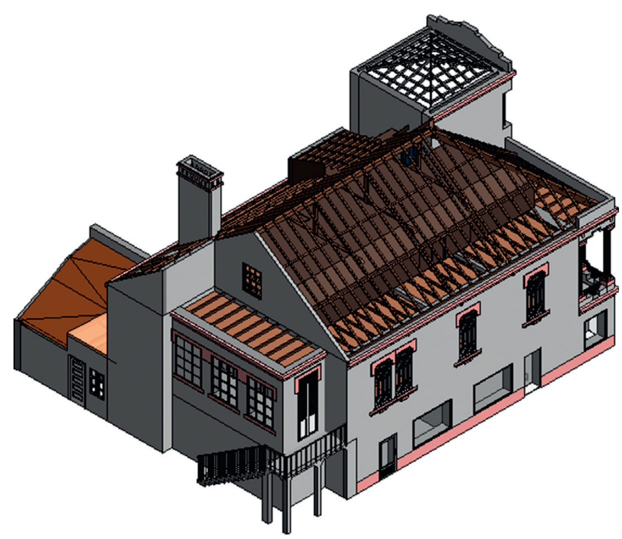


Figure 12: 3D view of the BIM model (rear and left elevation).

classification system Uniclass applied to constructive elements, constructive processes, materials, rooms, etc.

4.2.2. Family of Objects. Due to the technical detail and to unique and exclusive objects existence in the building, it was needed to model in place a high number of objects. In Figure 13, it is possible to show the creation of an object (window) in Revit.

It was not only essential to guarantee a precision level similar to reality but also essential to guarantee the family object parametrization, attributing geometric parameters and materials characterization.

4.2.3. Shared Parameters Application. The shared parameters were determined to be applied to add information to the model with information related to maintenance and conservation actions in heritage (Figure 14). Thus, 2 different parameters were created: general data and maintenance/inspection data.

The general data include the following:

(i) Facade element: yes/no
(ii) Facade: text
(iii) Floor level: text
(iv) Room: text
(v) Span: text

Maintenance/inspection data include the following:

(i) Construction date: integer
(ii) Date of last intervention: integer

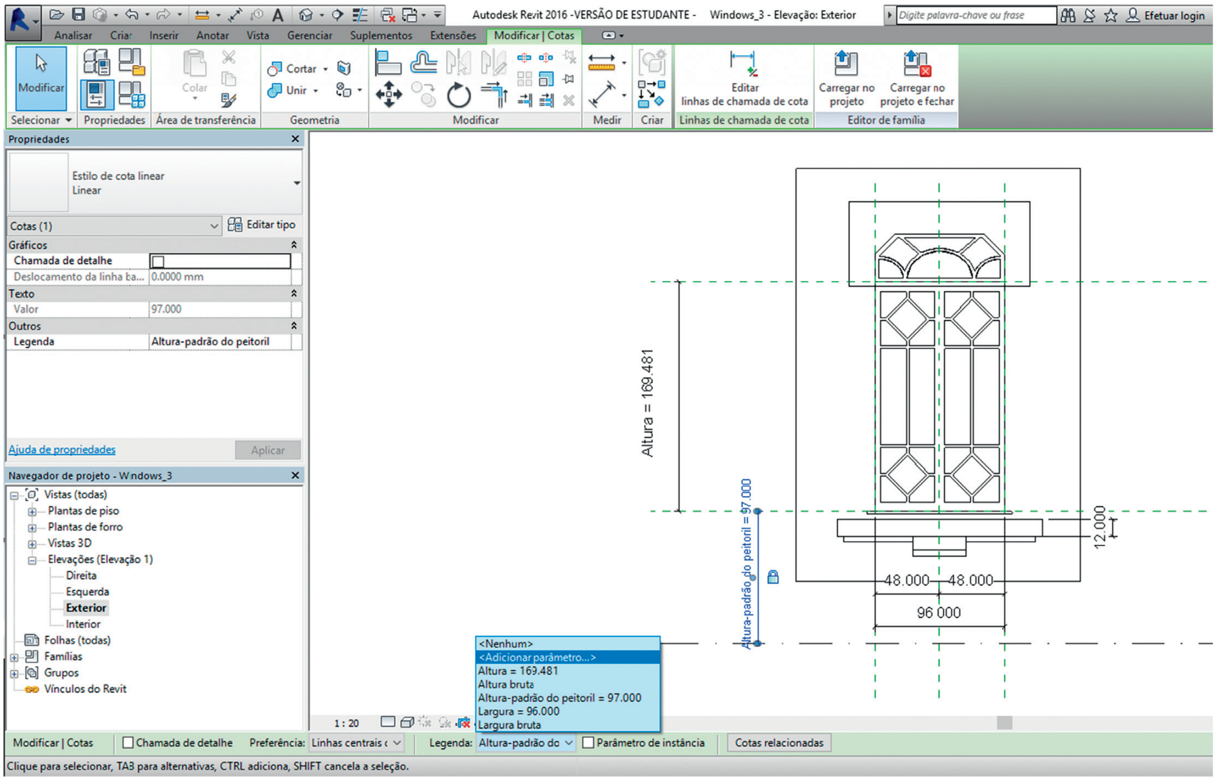


Figure 13: Revit interface for creating the window object family.

(iii) Notes: text

(iv) Pathologies report: text

(v) Maintenance cycle: number

(vi) Next inspection/maintenance: integer

These parameters were associated; however, it can be associated other parameters besides those.

After parameters association, the BIM model is ready to export all the information provided in the model to an external database. However, the information to complement the management model should not be provided just from shared parameters.

4.2.4. Drawings Associated with BIM Model. In the development of the management model through BIM application, drawings were developed such as, plans, sections, elevations, and constructive details. This application in the BIM model is an advantage since it allows creating automatic drawings from the model, and it can include annotations, comments, and hatches provided by the designer.

When the model is subjected to changes, the drawings are automatically updated in software. And this is an advantage of the automatic drawings created by the BIM model, which can decrease the inconsistency in the development of drawings.

These drawings perform an important role in the management model since the more the quality and quantity of the drawings developed, the less the difficulty of the project analysis by the user.

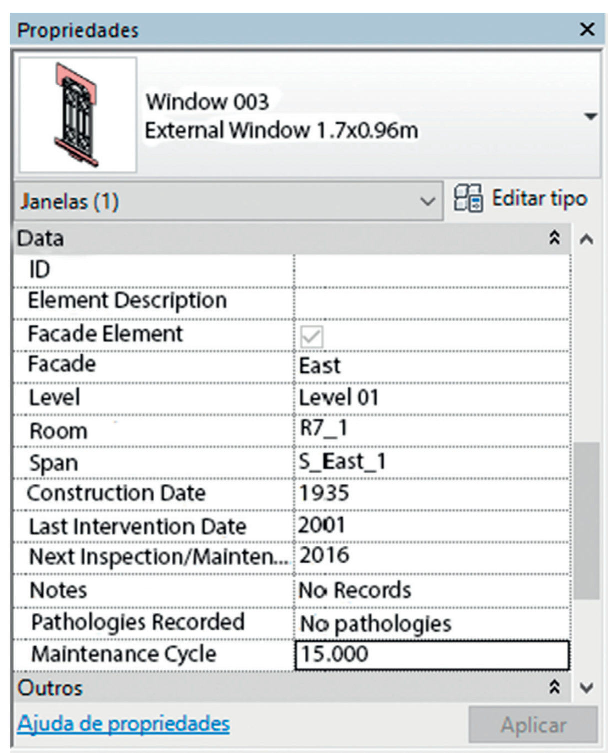


Figure 14: Shared parameters association.

4.3. Database. After the development of the BIM model, the exportation of parametric information to an external database is the next step.

The support database (GestHeritage) included in the management model was developed for supporting all the databases exported from BIM projects. For each project, GestHeritage will be associated with the, respectively, external database of the project.

Thus, information from database to the database management system Microsoft SQL Server with name "Project001_CasadeSanto António" was exported as shown in Figures 15 and 16.

This process was done through the plug-in DBLink that is able to extract all the parametric information of the constructive elements from Revit. This plug-in exports the linked tables, allowing the organisation of information in an interlinked and structured way, easier to the user. The exportation of the information from the BIM model to the external database is a high potential application; however, it is necessary the implementation of a management model to organize and catalogue all the information from the database in order to support the user during the maintenance and conservation actions in historical heritage.

4.4. API Connection. Since the management system is already developed, it is possible to start with the association of the projects with the system. Thus, the association of this case study model with the API developed through Visual Studio 2015 was done.

4.4.1. Elements Drivers. Taking into account that API works based on CRUD drivers, each element has its own driver providing specified information type and how it should be organized in the project database.

For example, for walls, the information that should be presented in inventory for the user and how it was organized is

(i) Object ID ⟶ *[dbo].[Walls]* ⟶ "ID";

(ii) Object Name ⟶ *[dbo].[WallType]* ⟶ "Name";

(iii) Length ⟶ *[dbo].[Walls]* ⟶ "Length";

(iv) Thickness ⟶ *[dbo].[WallType]* ⟶ "Thickness";

(v) Height ⟶ *[dbo].[Walls]* ⟶ "DisconnectedHigh";

(vi) Materials ⟶ *[dbo].[MaterialQuantities]* ⟶ "Material Id" ⟶ *[dbo].[Materials]* ⟶ "Name";

(vii) Structural use ⟶ *[dbo].[WallUsageEnums]* ⟶ "Name";

(viii) Object in facade ⟶ *[dbo].[Walls]* ⟶ "Element_in_Facade";

(ix) Facade ⟶ *[dbo].[Walls]* ⟶ "Facade";

(x) Floor ⟶ *[dbo].[Walls]* ⟶ "Floor";

(xi) Room ⟶ *[dbo].[Walls]* ⟶ "Compartment";

(xii) Span ⟶ *[dbo].[Walls]* ⟶ "Span";

(xiii) Construction date ⟶ *[dbo].[Walls]* ⟶ "Construction date";

(xiv) Date of the last intervention ⟶ *[dbo].[Walls]* ⟶ "Date of the last intervention";

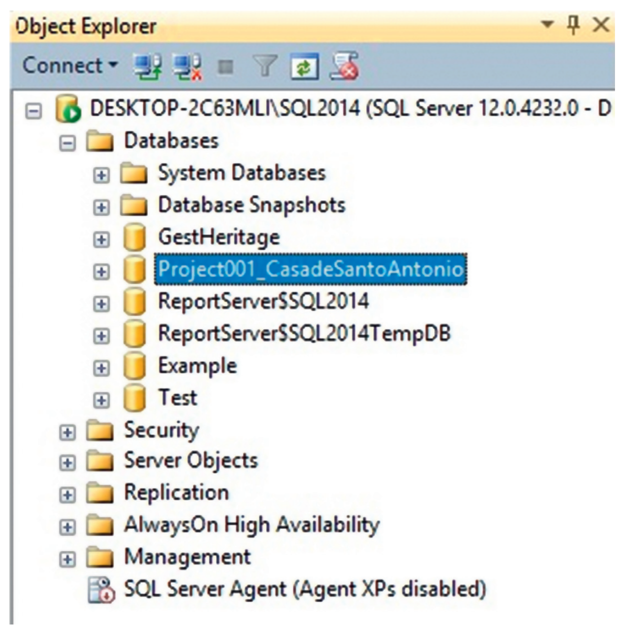


Figure 15: Microsoft SQL Server databases.

(xv) Observations ⟶ *[dbo].[Walls]* ⟶ "Observations";

(xvi) Recorded pathologies ⟶ *[dbo].[Walls]* ⟶ "Recorded pathologies";

(xvii) Maintenance cycle ⟶ *[dbo].[Walls]* ⟶ "Maintenance cycle";

(xviii) Next inspection/Maintenance ⟶ *[dbo].[Walls]* ⟶ "Next inspection/Maintenance".

Through these parameters, it was possible to develop the drivers. However, it is highlighted that these parameters can easily be modified according the user needs.

4.4.2. Provision of Databases. Before the application of the case study in web application, it was needed to feed the support database (GestHeritage) with all adequate information and data for management. This information includes drawings developed by the BIM model and all complement information to categories of the management model (reports, BIM model). Figure 17 shows an example of association of drawings with the project of the case study.

4.4.3. Application Web Involvement. The database in the application web turns possible the visualisation and edition of the information from the BIM model by the user. The information must be structured, organized, and concise in order to provide the adequate accessibility for user.

With the association of the database of the project with the management model developed, the implementation of dynamic tables developed was possible, when it connects the application web with drivers, for every driver involved in this case study.

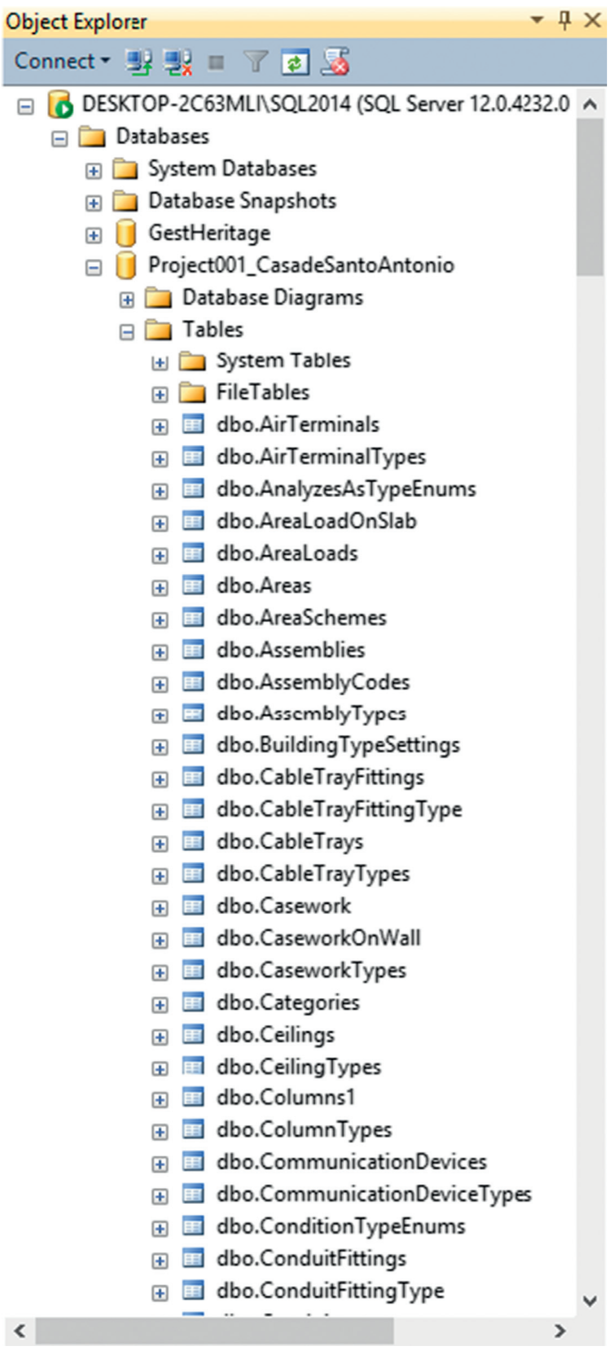


Figure 16: Tables generated by DBLink from the case study.

Thus, it is possible to not only see just the information included in exported database from the BIM model but also edit this information directly from the database and consequently from the BIM model. However, this information editing is just possible by accredited users (Admin or ReadWrite).

The result is based on a dynamic table with the requisition system (Get) and transmission (Put) of the database and contains the advantage of deliver for user, just the essential information of the element, as the example in Figure 18.

With the application of the management model of this case study, it was possible to verify and validate the usefulness of the heritage management system. It is also verified that there exist an easy access of the user to the information of the BIM model and also a complement system of management of information elements (drawings, documents, and reports) in the digital format. Thus, it is possible to guarantee a reliable library of information and with easy access to user, decreasing the information loss and its outdating.

5. Conclusions

This work demonstrates the necessity of development and implementation of a strategy of intervention which contributes to the preservation and maintenance of heritage, through the application of a management system able to answer this need in a reliable process.

The practical application of the management system can revolutionize the way the management and maintenance of historical heritage is seen. It is allowed not only to reorganize and structure all Portuguese historical heritages but also to manage them, assuring its constant and updated maintenance, avoiding its degradation.

The success of the implementation of this management system proves its ability to adequate the management for any kind of historical building to digital format. This ability guarantees a decrease of the information lost and improves the access by the users to this information.

BIM shows that is a methodology able to meet the user's needs in an every-day more challenging society.

In practice, BIM is still less explored in the implementation of management systems with success. This process opens an opportunity to this model in the scope of the maintenance, conservation, and refurbishment for heritage and for all existent buildings.

Besides this, it is possible to have a three-dimensional parametric and detailed model of the building, providing the decision-making more reliable and quicker.

The connection of the BIM model and database is done through DBLink included in Revit Autodesk and performs an important role in the developed management model. However, the functionality of the plug-in demands an extraperformance approach since it should predict the exportation not only of the parametric data, but also of drawings associated with the project, which it cannot do. The disability to update automatically and the changes between databases and BIM model are other disadvantages of the DBLink. DBLink should have the ability to update automatically, instead of the manual command inventory user.

The practical application of this management model achieves the expectations designed for this work since it was possible to update the way how the management of heritage was done for a management system which follows a concept of new information technologies. Thus, it is possible to guarantee a reliable update of the data and information reached by the user.

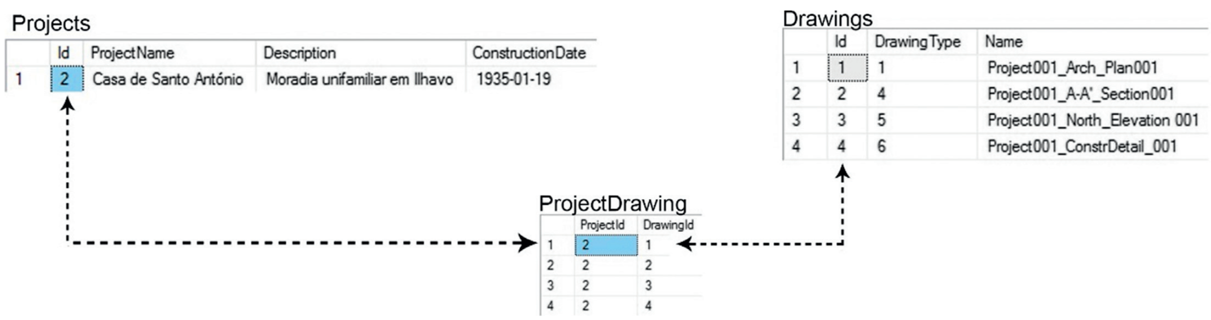
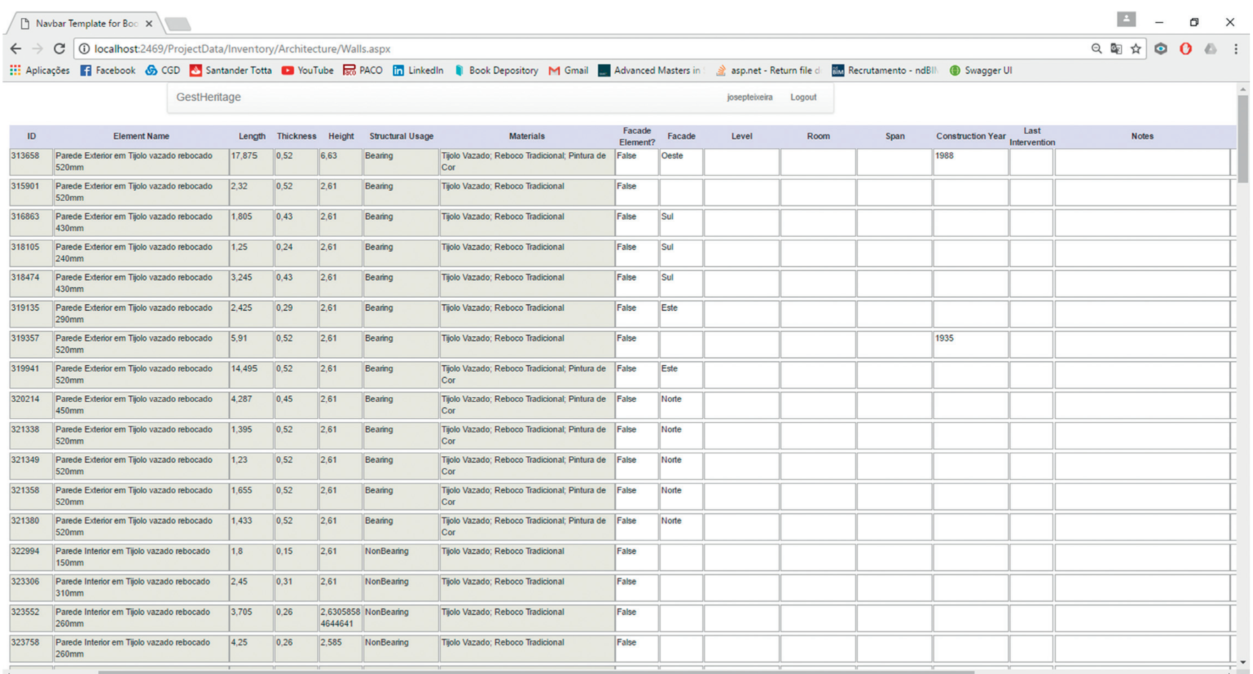


Figure 17: Association of the case study project with the respective drawings.



ID	Element Name	Length	Thickness	Height	Structural Usage	Materials	Facade Element?	Facade	Level	Room	Span	Construction Year	Last Intervention	Notes
313658	Parede Exterior em Tijolo vazado rebocado 520mm	17,875	0,52	6,63	Bearing	Tijolo Vazado; Reboco Tradicional; Pintura de Cor	False	Oeste				1988		
315901	Parede Exterior em Tijolo vazado rebocado 520mm	2,32	0,52	2,61	Bearing	Tijolo Vazado; Reboco Tradicional	False							
316863	Parede Exterior em Tijolo vazado rebocado 430mm	1,805	0,43	2,61	Bearing	Tijolo Vazado; Reboco Tradicional	False	Sul						
318105	Parede Exterior em Tijolo vazado rebocado 240mm	1,25	0,24	2,61	Bearing	Tijolo Vazado; Reboco Tradicional	False	Sul						
318474	Parede Exterior em Tijolo vazado rebocado 430mm	3,245	0,43	2,61	Bearing	Tijolo Vazado; Reboco Tradicional	False	Sul						
319135	Parede Exterior em Tijolo vazado rebocado 290mm	2,425	0,29	2,61	Bearing	Tijolo Vazado; Reboco Tradicional	False	Este						
319357	Parede Exterior em Tijolo vazado rebocado 520mm	5,91	0,52	2,61	Bearing	Tijolo Vazado; Reboco Tradicional	False					1935		
319941	Parede Exterior em Tijolo vazado rebocado 520mm	14,495	0,52	2,61	Bearing	Tijolo Vazado; Reboco Tradicional; Pintura de Cor	False	Este						
320214	Parede Exterior em Tijolo vazado rebocado 450mm	4,287	0,45	2,61	Bearing	Tijolo Vazado; Reboco Tradicional; Pintura de Cor	False	Norte						
321338	Parede Exterior em Tijolo vazado rebocado 520mm	1,395	0,52	2,61	Bearing	Tijolo Vazado; Reboco Tradicional; Pintura de Cor	False	Norte						
321349	Parede Exterior em Tijolo vazado rebocado 520mm	1,23	0,52	2,61	Bearing	Tijolo Vazado; Reboco Tradicional; Pintura de Cor	False	Norte						
321358	Parede Exterior em Tijolo vazado rebocado 520mm	1,655	0,52	2,61	Bearing	Tijolo Vazado; Reboco Tradicional; Pintura de Cor	False	Norte						
321380	Parede Exterior em Tijolo vazado rebocado 520mm	1,433	0,52	2,61	Bearing	Tijolo Vazado; Reboco Tradicional; Pintura de Cor	False	Norte						
322994	Parede Interior em Tijolo vazado rebocado 150mm	1,8	0,15	2,61	NonBearing	Tijolo Vazado; Reboco Tradicional	False							
323306	Parede Interior em Tijolo vazado rebocado 310mm	2,45	0,31	2,61	NonBearing	Tijolo Vazado; Reboco Tradicional	False							
323552	Parede Interior em Tijolo vazado rebocado 260mm	3,705	0,26	2,6305858 4644641	NonBearing	Tijolo Vazado; Reboco Tradicional	False							
323758	Parede Interior em Tijolo vazado rebocado 260mm	4,25	0,26	2,585	NonBearing	Tijolo Vazado; Reboco Tradicional	False							

Figure 18: Dynamic table of the element walls of the case study in the web application.

Although this work was developed and applied to the management of heritage, it is essential to highlight the practical application of this model to existent buildings, namely, without any historical value but with conservation or refurbishment justified in medium/long term.

So, the model developed and proposed can help management entities, such as general direction of historical heritage, to have a resource to maintenance and conservation of heritage, allowing its management and maintenance through a digital platform.

The practical usefulness of this management model will enhance the use of all existent resources in the heritage.

The information will be stored in the digital format in a management platform able to manage all the information related with projects, assuring the interoperability between system and user.

Besides this, these models are a solution to the existent gaps and incoherence in the drawings through BIM methodology. Therefore, there is a decrease of the incoherence in the draw parts, allowing us to have and manage contextualized and consistent drawings.

The documentation and reports are also included in the model, so it is possible to inform the user about conditions, documents details, and historical framework of the project supporting the user to know about the evolutive situation of the project.

Finally, this management system highlights the management of the elements of the project, improving a management of detail and parametric maintenance in project inventory.

This inventory includes all constituent elements, allowing not only a general maintenance of the project, but also a partial maintenance of the elements, rooms, facades, for a reliable and focus maintenance management.

It is possible to conclude that the application of the model was a success and all the objectives proposed were completed. The work presented and the work analysed in the literature review show that HBIM applications are often needed to jointly perform different kinds of analysis and to properly connect the related environments and formats; thus, it is clear why there is a need to focus the development of HBIM applications with a heterogeneous multi-models' interoperability with a standardised approach.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] J. P. Bernardes, L. F. Oliveira, R. Moreira, and T. Valente, "Património Cultural Edificado : reflexões em torno da gestão do Património Classificado," *Lusophone Journal of Cultural Studies*, vol. 2, pp. 34–52, 2014.

[2] A. Forster and B. Kayan, "Maintenance for historic buildings: a current perspective," *Journal of Quality in Maintenance Engineering*, vol. 27, no. 3, pp. 210–229, 2009.

[3] E. Dezen-Kempter, "Digital Dialogues : integration of documentary data in model based information systems for the conservation," in *Proceedings of the XVII Conference of the Iberoamerican Society of Digital Graphics-SIGraDi: Knowledge-Based Design*, vol. 1, pp. 293–296, 2014.

[4] S. Fai, K. Graham, T. Duckworth, N. Wood, and R. Attar, *Building Information Modelling and Heritage Documentation Carleton Immersive Media Studio*, Azrieli School Of Architecture And Urbanism, Ottawa, Canada, 2011.

[5] A. Akanmu, O. Olatunji, P. E. D. Love, D. Nguyen, and J. Matthews, "Auto-generated site layout: an integrated approach to real-time sensing of temporary facilities in infrastructure projects," *Structure and Infrastructure Engineering*, vol. 12, no. 10, pp. 1243–1255, 2015.

[6] É. Meyer, P. Grussenmeyer, J.-P. Perrin, A. Durand, and P. Drap, "A web information system for the management and the dissemination of Cultural Heritage data," *Journal of Cultural Heritage*, vol. 8, no. 4, pp. 396–411, 2007.

[7] A. Guarnieri, F. Pirotti, and A. Vettore, "Cultural heritage interactive 3D models on the web: an approach using open source and free software," *Journal of Cultural Heritage*, vol. 11, no. 3, pp. 350–353, 2010.

[8] A. D. Styliadis, "Digital documentation of historical buildings with 3-d modeling functionality," *Automation in Construction*, vol. 16, no. 4, pp. 498–510, 2007.

[9] G. Pavlidis, A. Koutsoudis, F. Arnaoutoglou, V. Tsioukas, and C. Chamzas, "Methods for 3D digitization of cultural heritage," *Journal of Cultural Heritage*, vol. 8, no. 1, pp. 93–98, 2007.

[10] H. M. Yilmaz, M. Yakar, S. A. Gulec, and O. N. Dulgerler, "Importance of digital close-range photogrammetry in documentation of cultural heritage," *Journal of Cultural Heritage*, vol. 8, no. 4, pp. 428–433, 2007.

[11] H. Haggrén, K. Koistinen, H. Junnilainen, and A. Erving, *Photogrammetric Documentation and Modeling of na Archaelogical Site: The Finnish Jabal Project*, The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Mestre-Venice, Italy, 2005.

[12] P. Grussenmeyer and J. Yasmine, "The restoration of beaufort castle (South-Lebanon). A 3D restitution according to historical documentation," in *Proceedings of CIPA XIXth International Symposium of New Perspectives to Save Cultural Heritage*, Antalya, Turkey, September 2003.

[13] M. Bassier, G. Hadjidemetriou, M. Vergauwen, N. Van Roy, and E. Verstrynge, "Implementation of scan-to-BIM and FEM for the documentation and analysis of heritage timber roof structures," in *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection. EuroMed 2016. Lecture Notes in Computer Science*, M. Ioannides, Ed., Springer, Cham, Switzerland, 2016.

[14] S. Portier, J. Maltret, and J. Zoller, "Computer graphics: asssistance for archaelogical hypotheses," *Automation in Construction*, vol. 9, no. 1, pp. 117–128, 2000.

[15] F. López, P. Lerones, J. Llamas, J. Gómez-García-Bermejo, and E. Zalama, "A review of heritage building information modeling (H-BIM)," *Multimodal Technologies and Interaction*, vol. 2, no. 2, p. 21, 2018.

[16] D. Pasini, V. Caffi, B. Daniotti, S. Lupica Spagnolo, and A. Pavan, "The INNOVance BIM library approach," *Innovative Infrastructure Solutions*, vol. 2, no. 1, p. 15, 2017.

[17] M. Tolentino and B. Feitosa, *A Utilização de Tecnologias Digitais Na Documentação do Patrimônio Arquitetônico*, 2014.

[18] A. Costin, A. Adibfar, H. Hu, and S. S. Chen, "Building Information Modeling (BIM) for transportation infrastructure – literature review, applications, challenges, and recommendations," *Automation in Construction*, vol. 94, pp. 257–281, 2018.

[19] J. D. R. T. Soares, *A Metodologia BIM-FM aplicada a um caso prático*, 2013.

[20] K. M. Kensek, "BIM: "I" is for interoperability. BIM is more, chapter 3: data exchange and interoperability," in *Technical Design Series: Building Information Modeling*, pp. 83–89, Routledge, Abingdon, UK, 2016.

[21] C. A. Jacoski, *A Utilização de Arquivos IFC Para a Integração de Dados Junto à Indústria da Construção*, 2002.

[22] F. Pinho, *Norma BIM Portuguesa*, Tese de Mestrado em Engenharia Civil, Faculdade de Ciências e Tecnologia, Univeridade de Coimbra, Coimbra, Portugal, 2015.

[23] V. Bazjanac, *Impact of the U.S. National Building Information Model Standard (NBIMS) on Building Energy Performance Simulation*, pp. 1377–1382, Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 2007, http://escholarship.org/uc/item/3v95d7xp.pdf%5Cnhttp://escholarship.org/uc/item/3v95d7xp.

[24] M. J. F. Silva, F. Salvado, P. Couto, and Á. V. e. Azevedo, "Roadmap proposal for implementing building information modelling (BIM) in Portugal," *Open Journal of Civil Engineering*, vol. 6, no. 6, pp. 475–481, 2016.

[25] A. A. Costa, *O paradigma BIM e a Normalização Como fator de competitividade*, Instituto Português da Qualidade (IPQ), Caparica, Portugal, 2014, http://www1.ipq.pt/PT/Site/Destaques/Historico/Paradigma-BIM-e-a-normalizacao-como-fator-de-competitividade.aspx.

[26] F. Re Cecconi, S. Maltese, and M. C. Dejaco, "Leveraging BIM for digital built environment asset management," *Innovative Infrastructure Solutions*, vol. 2, no. 1, p. 14, 2017.

[27] R. Volk, J. Stengel, and F. Schultmann, "Building Information Modeling (BIM) for existing buildings - literature review and future needs," *Automation in Construction*, vol. 38, pp. 109–127, 2013.

[28] C. Dore and M. Murphy, "Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites," in *Proceedings of the 2012 18th International Conference on Virtual Systems and Multimedia, VSMM 2012: Virtual Systems in the Information Society*, pp. 369–376, Milan, Italy, September 2012.

[29] M. Murphy, E. McGovern, and S. Pavia, "Historic building information modelling (HBIM)," *Structural Survey*, vol. 27, no. 4, pp. 311–327, 2009.

[30] L. M. Khodeir, D. Aly, and S. Tarek, "Integrating HBIM (heritage building information modeling) tools in the application of sustainable retrofitting of heritage buildings in Egypt," *Procedia Environmental Sciences*, vol. 34, pp. 258–270, 2016.

[31] G. Saygi and F. Remondino, "Management of architectural heritage information in BIM and GIS: state-of-the-art and future perspectives," *International Journal of Heritage in the Digital Era*, vol. 2, no. 4, pp. 695–713, 2013.

[32] M. Murphy, E. McGovern, and S. Pavia, "Historic building information modelling-adding intelligence to laser and image based surveys," in *Proceedings of 38th ISPRS-International Archives*, pp. 2–4, Trento, Italy, March 2011, http://adsabs.harvard.edu/abs/2011ISPAr3816W...1M.

[33] A. Baik, "From point cloud to jeddah heritage BIM nasif historical house - case study," *Digital Applications in Archaeology and Cultural Heritage*, vol. 4, pp. 1–18, 2017.

[34] D. Oreni, R. Brumana, and B. Cuca, "Towards a methodology for 3d content models: the reconstruction of ancient vaults for maintenance and structural behaviour in the logic of bim management," in *Proceedings of 2012 18th International Conference on Virtual Systems and Multimedia*, pp. 475–482, Milan, Italy, 2012.

[35] S. Logothetis and E. Stylianidis, "BIM Open Source Software (OSS) for the documentation of cultural heritage," *Virtual Archaeology Review*, vol. 7, no. 15, pp. 28–35, 2016.

[36] P. Pauwels, R. Bod, D. Di Mascio, and R. De Meyer, "Integrating building information modelling and semantic web technologies for the management of built heritage information," in *2013 Digital Heritage International Congress (DigitalHeritage)*, pp. 481–488, IEEE, Marseille, France, 2013.

[37] B. Caires and I. C. BIMMS, "Data Management & Comunication. BIM is More," *Chapter 05: Application, Subchapter 5.3, BIM Project Implementation Lessons Learned*, pp. 90-91, 2016.

[38] P. M. Lerones, D. O. Vžlez, F. G. Rojo, J. G. Garcia-Bermejo, and E. Z. Casanova, "Moisture detection in heritage buildings by 3D laser scanning," in *Studies in Conservation*, Maney Publishing, Leeds, UK, 2016.

[39] F. J. López, P. Martin Lerones, J. Llamas, J. Gómez-García-Bermejo, and E. Zalama, "Semi-automatic generation of BIM models for cultural heritage," *International Journal of Heritage Architecture: Studies, Repairs and Maintence*, vol. 2, no. 2, 2017.

[40] F. Maietti, R. Di Giulio, E. Piaia, M. Medici, F. Ferrari, and B. Turilazzi, "Integrated data capturing requirements for 3D semantic modelling of cultural heritage: the inception protocol," *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 42, pp. 251–257, 2018.

[41] L. F. Ramos, M. G. Masciotta, M. J. Morais et al., "HeritageCARE:preventive conservation of built cultural heritage in the South-West Europe, book: innovative built heritage models," K. van Balen and A. Vandesande, Eds., CRC Press, Boca Raton, FL, USA, 2018.

[42] A. Baik and J. Boehm, "Building information modelling for historical building Historic Jeddah - Saudi Arabia," in *Proceedings of 2015 Digital Heritage International Congress, Digital Heritage*, pp. 125–128, Granada, Spain, 2016.

[43] R. Gamelas, "Caracterização e monitorização para reabilitação da sede da InovaDomus," M.S thesis. Universidade de Aveiro, Aveiro, Portugal, 2013, https://ria.ua.pt/handle/10773/12903.

[44] InovaDomus, *Relatório de Caracterização Estrutural da Sede da InovaDomus*, 2016.

[45] A. Styliadis, *Digital documentation of monuments and sites with 3D geometry and qualitative information*, PhD Thesis, Faculty of Rural and Surveying Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece, 1997.

Hindawi
Advances in Civil Engineering
Volume 2018, Article ID 5478381, 14 pages
https://doi.org/10.1155/2018/5478381

Research Article

A Study on the BIM Evaluation, Analytics, and Prediction (EAP) Framework and Platform in Linked Building Ontologies and Reasoners with Clouds

Yongwook Jeong

Department of Architecture, College of Engineering, Sejong University, Seoul 05006, Republic of Korea

Correspondence should be addressed to Yongwook Jeong; yjeong@sejong.ac.kr

Received 22 June 2018; Revised 2 September 2018; Accepted 25 September 2018; Published 5 November 2018

Guest Editor: Tatjana Vilutiene

Rigorous research and practical experience have allowed building information modeling (BIM) to be successfully adopted in the traditional design process without being severely cumbersome. However, there has been less focus on the connectivity and convergence of multiple types of BIM data or even the connectivity among non-BIM data, such as natural language and image/video data. The connectivity of BIM data means more than the syntactical correlations among them. This paper considers how BIM should be redefined to process BIM data as linked semantic data from the perspective of building information management and employ recent advances in the evaluation, analytics, and prediction (EAP) methodology for linked building ontologies and reasoners.

1. Introduction

Initially, building information modeling (BIM) largely classified domains to reflect the life cycle of buildings above a certain scale. The classified domains included building control; plumbing protection; structural elements; structural analysis; heating, ventilation, and air conditioning (HVAC); electrical; architecture; and construction management. The fourth revision of the Industry Foundation Classes (IFCs) was officially announced recently; this is the result of a focus on the interoperability of domains covered by the entire architecture, engineering, and construction (AEC) industry. The current version of each domain was reached through standardization whenever new requirements appeared. IFC is relatively complete from the perspective of BIM. This allows BIM to be introduced more frequently domestically and globally based on various academic trials and studies beyond the commercial needs driven by industry. The visualization of related legislation, including regulations on three-dimensional land geospatial information construction from the Ministry of Land, Infrastructure, and Transport, has also accelerated the introduction of BIM.

BIM is associated with advances in conventional computer-aided design (CAD) software. AutoDesk's products, which are regarded as a de facto standard in the AEC industry, include various functions, such as CAD, computer-aided engineering (CAE), and computer-aided manufacturing (CAM) to assist BIMs. As of 2015, more than ten software programs directly or indirectly assist BIM. With IFC2.x up to the recent 4.x, companies are waging a fierce competition to advance and innovate in the industry while maintaining backward compatibility. While the importance and utility of BIM represented by the IFC have been on the rise, the complexity of the IFC itself has also increased. Thus, the aspects of collecting, storing, analyzing, and utilizing data in various types and sizes still depend on monolithic computing resources (i.e., standalone computing as opposed to distributed computing). In addition, during the life cycle of a building, large-scale data that are available after construction (e.g., data collected by closed-circuit televisions (CCTVs) installed in the building) are not used at all. Even the IFC does not consider various data that can be extracted from images or videos, so there is no room for "connections" using such data.

The main reason for using BIM is that accurate geometric data for a building can be deployed in an integrated environment [1]. Economically, BIM can increase the cost estimation accuracy, shorten the construction period, and reduce changes that affect the budget by up to 40% [2]. Consequently, the positive functions of BIM derived through various case studies help predict the building costs and construction period more accurately through clearly defined data obtained from design through construction. This is because the purpose of BIM is to completely exclude uncertainty from consideration. As Rittel previously indicated, however, the problem of planning in architecture/construction is the so-called "wicked problem" [3]. Therefore, uncertainty cannot be eliminated. More in depth, studies on methods for managing the uncertainty are required.

The leading academic disciplines to manage uncertainty are economics and management. The field of prescriptive analytics, which aims to predict the future and find an optimal alternative by collecting factual data and using an analysis model, is at the cutting edge of such research. Some studies have tried to use the conventional BIM model for the initial design stage of a building to analyze the possible risks, but management methods that provide more sophisticated analysis using connections to new data beyond the model are still in the rudimentary stage because they are limited to the model. In this paper, BIM is examined from the perspective of building information management by defining information from the user's point of view and converting it to an ontology, which is usable and has web-scale expandability beyond a simple model. A BIM evaluation, analytics, and prediction (EAP) platform capable of collecting, storing, processing, and analyzing BIM data in an integrated manner is also presented.

2. Related Work

2.1. Background and Analytics Definition. Management researchers have made significant efforts to manage the issue of uncertainty. Analytics can be defined as a series of technologies that help with decision making by collecting factual data, examining them from various perspectives, and predicting the future based on the results. Business analytics, which is represented by enterprise resource planning (ERP), was developed to predict future management situations more accurately by collecting and storing all data that can be defined in management activities and analyzing them through various statistical techniques [4].

With BIM, these three types of analytics can be used for decision making as entire project progresses. Descriptive analytics is used to reproduce the relationship between each object and is accomplished by various BIM software programs currently used in the mainstream. Predictive and prescriptive analytics are used to predict costs and measure the energy consumption performance, especially in the initial design stage with high uncertainty [5].

2.2. BIM and Ontologies in the AEC Industry. It is difficult to deny that IFCs are an output of significant efforts to capture and document domain knowledge throughout the AEC industry. However, this means that in order to use IFC correctly, there should be a way to find and retrieve resources that correspond to individual domain knowledge among the existing classes. It is also almost impossible to extend the vocabularies to keep up with fast-paced domain knowledge change.

The modeling focus of IFC is quite different from modeling ontologies, in which, IFC aims to set up a comprehensive set of data exchanges, whereas ontology is primarily focused on reserving semantics and making acquired and formalized knowledge reusable. The relationships between concrete classes in IFC are already defined (e.g., IS_A and PART_OF). Ontologies, however, allow users to define the relationships freely (e.g., belongsTo and oppositeTo). Thus, organizing the IFCs with higher semantic languages to facilitate shared understanding among the participants is necessary [6, 7].

The first step toward making ontological IFC is to create an XML format of IFC. ifcXML, aecXML, BLIS-XML, and others have aimed to extend, integrate, or complement IFC with XML [8]. Other approaches to add an ontological layer to the IFCs have been developed (e.g., STABU Lexicon, eConstruct, and ISTforCE). These approaches focused on developing a mediator between ontologies and the IFCs in the form of a web service. More direct implementation of ontology for IFC was proposed by Zhang and Issa [9] as a part of constructing Inteligrid, which aims to support dynamic virtual organizations through a set of ontology-based grid-enabled services. They took two approaches. First, they tried to use a standardized method with XSLT technology and to transform the Part 28 XML schema of the IFCs 2 × 2 into an OWL file with an XSLT. The difficulty in using this approach was to resolve the structural difference between the XML schema and OWL. Secondly, they derived the OWL notation directly from the original EXPRESS schema format of the IFCs using their proprietary parser. They reported that they maintain an ontology with over 850 classes and more than 4000 overall frames.

Beetz et al. took an additional step and proposed a semantic web service framework structure that uses ifcOWL [8]. This system uses the IFC model stored in ifcXML, and each user can obtain an answer by creating a query such as "What is the height of the girder on the first floor?" using a standardized method. Although this method can be used without difficulty in few environments, particularly those that have low complexity, it is not suitable for multiple users and a large-scale project.

According to Pauwels et al. [10], other elements that make up the semantic web included knowledge representation, which constitute the ontology, and software agents capable of finding content and automatically constructing and providing services on behalf of people. There are several important reasons for converting IFC to an XML-based ontology to express structured information in a form that can be processed by computers: (1) data can be prevented from being dependent on certain applications, (2) intelligence can be provided to the expression form itself, and (3) new facts can be inferred and converted to knowledge through the factual data-based expression form and structured query.

2.3. BIM and Big Data. The concept and technology of big data are only briefly discussed here because of space limitations. The term "big data" refers to data with properties, such as the volume, variety, and velocity, that are difficult or impossible for a single system to collect, process, store, analyze, and utilize [11]. In terms of the data types, the most important elements are structured data (e.g., databases and data warehouses) and unstructured data (e.g., text composed of natural languages, images, and videos). Among various industries, analysis can improve the production yield for manufacturing, which uses various high-precision sensors in large quantities. Recommendation services of social networks, such as Facebook, Twitter, and LinkedIn, based on the relationship-oriented collection, storage, processing, and analysis of data are generally considered successful at defining the meaning, form, and utilization of big data.

Hadoop, which was developed as open-source software in 2005, is a representative big data technology. It is an object-oriented distributed processing platform and has been established as an industry standard after its capabilities for collecting, storing, and processing Web-scale data were verified. Various technologies have been developed to overcome the properties and limits of Hadoop, NoSQL, and NewSQL [12]. Relational database management systems (RDBMSs) for data storage, distributed data stream processing technology for real-time processing/analysis, in-memory technology capable of processing/analyzing in memory for high-speed data processing, and large-scale machine learning and artificial intelligence technology for intelligent analysis are expected to be established as standard technologies for big data in the future.

Although technologies for storing and processing big data are important, establishing and verifying a model for data analysis are not dependent on the size or quantity of data. Therefore, academic organizations have recently been proposing optimal analysis methods that consider the type, form, and size of data. BIM data include the properties of big data (e.g., large scale, composed of structured and unstructured data, and placement and real-time processing are performed simultaneously). Because processing and analysis through the existing standalone system decreases in productivity as the scale of BIM data increases, attempts have been made to approach BIM with the big data concept.

A sensor network was installed in a large building, and a BIM system collected, processed, and analyzed the large amount of generated data to provide the occupants with higher thermal comfort while minimizing the energy consumption [13]. This focus on the volume and velocity provides an important clue to data processing for occupant-centric building design.

Cloud computing is often mentioned as a computing resource for processing big data. This is because big data are not always present, so data collected for a certain period can be processed within a short period by using cloud computing, which utilizes combined computing power. Jiao et al. utilized the concept of project data as a service and connected BIM and a social networking service (SNS) [14]. They proposed a management method that integrates various forms of data generated in each area (e.g., architecture, engineering, construction, and facility management) to be shared by the entire project through the cloud.

3. BIM, Linked Building Ontology, and Big Data

3.1. BIM Data and Ontology. The BIM data characteristics that are discussed in this study are based on the fourth version of IFC [15], which was produced for BIM interoperability [16]. IFC of the International Alliance of Interoperability (IAI) is based on the object-oriented parametric product model. Therefore, IfcRoot is defined at the top, and all other objects are defined based on this object (Table 1).

Just as IFC is oriented to interoperability, XML shares the same goal for the interoperability of documents on the Internet, such as the World Wide Web Consortium (W3C). Therefore, IFC currently uses various XML expressions. Not only is ifcXML defined by the IAI, but also ifcOWL [17] which is based on the Resource Description Framework (RDF) [18, 19] is also defined to include semantic information in XML and Web Ontology Language (OWL) and is commonly used [20].

3.2. BIM and the Ontology Units. Linked building ontologies have the highest degree of freedom, in which terms can be newly defined depending on the needs of the user. However, different definitions for the same word may increase confusion in the AEC industry, where collaboration is required. One approach is the publish/subscribe method, where a kind of repository is constructed for every object (including entities) to be used that is shared through mutual agreement by every collaborating unit in [22].

It is assumed that there are four common ontological units, as illustrated in Figure 1: Building unit (BU) (house, school, hospital, office, etc.), Space unit (SU) (room, bedroom, bathroom, ward, lobby, etc.), Construction unit (CU) (slab, partition, floor, wall, window, door, etc.), and Functional unit (FU) (furniture, equipment, etc.). The entities within each unit are defined in Figures 2–5.

As stated earlier, RDF and XML are methods for defining an ontology. RDF has three components: a subject, predicate, and object. However, it can also be expressed by a graph composed of nodes and edges to further emphasize connectivity. Various commercial/open-source graph databases have been developed to process this kind of data in large quantities. In particular, graph databases specialized for RDF and capable of processing more than one trillion nodes are being developed (e.g., AllegroGraph). Since the existing IFC model can be automatically converted by using tools, such as ifc-to-RDF, the user can save the RDF in the shared space when publishing or subscribing. Sharing various data by multiple users requires a suitable process model, as shown in Figure 6.

4. BIM EAP Framework and Platform of Linked Building Ontologies and Reasoners with Clouds

4.1. The Components of the BIM EAP Platform. As noted earlier, BIM has the three V's of big data: volume, variety,

Table 1: IFCEXPRESS, ifcXML, and ifcOWL [21].

IFCEXPRESS	ENTITY IfcRoot ABSTRACT SUPERTYPE OF(ONEOF(IfcObjectDefinition, IfcPropertyDefinition, IfcRelationship)); GlobalId: IfcGloballyUniqueId; OwnerHistory: OPTIONAL IfcOwnerHistory; Name: OPTIONAL IfcLabel; Description: OPTIONAL IfcText; UNIQUE UR1: GlobalId; END_ENTITY;
ifcXML	<xs:element name="IfcRoot" type="ifc:IfcRoot" abstract="true" substitutionGroup="ifc:Entity" nillable="true"/> <xs:complexType name="IfcRoot" abstract="true"> <xs:complexContent> <xs:extension base="ifc:Entity"> <xs:sequence> <xs:element name="OwnerHistory" type="ifc:IfcOwnerHistory" nillable="true" minOccurs="0"/> </xs:sequence> <xs:attribute name="GlobalId" type="ifc:IfcGloballyUniqueId" use="optional"/> <xs:attribute name="Name" type="ifc:IfcLabel" use="optional"/> <xs:attribute name="Description" type="ifc:IfcText" use="optional"/> </xs:extension> </xs:complexContent> </xs:complexType>
ifcOWL	<owl:ObjectProperty rdf:about="http://buildingsmart.org/ontology/IFC-Name_of_IfcRoot> <rdf:type rdf:resource="> <ns0:label>Name</ns0:label> <ns0:range rdf:resource="> <ns0:domain rdf:resource="> </owl:ObjectProperty>

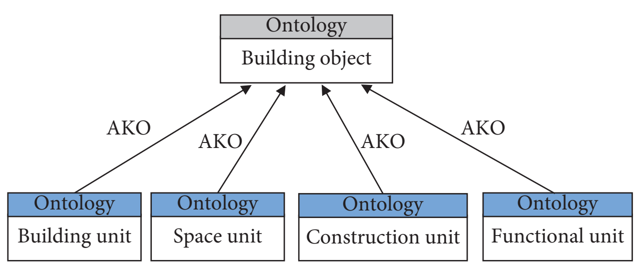


Figure 1: Building object ontology.

and velocity. An analytics framework for BIM is required along with an open-source platform to satisfy various purposes. Figure 7 shows the components of the BIM EAP framework and the functions of the platform. The Hadoop framework at the bottom collects and stores BIM-related data of various kinds and speeds. It plays the role of the data collecting/processing layer in charge of preprocessing for data analysis according to the user's requirements.

The functions of MapReduce for processing large-scale batch data, Spark framework for processing the relationships between data at a high speed, and Drill or Impala for user interactive analytics are located in this framework. As a data analytics layer, the analytics framework divides BIM data into structured and unstructured types, supports a series of workflows capable of applying analysis algorithms depending on the nature of data, and includes some machine learning functions, such as deep learning.

The BIM EAP platform supports an increase in versatility. The visualization framework corresponds to a data presentation layer and visualizes the workflow used to store and process data or the data analysis results. In this case, the expression of three-dimensional (3D) geometry is important because of the nature of BIM data. This framework supports level of detail (LOD) (technology to adjust details expressed according to the size of the 3D model displayed on a computer screen) and cross-platform capabilities by using WebGL, which is the standard for 3D visualization, and its web standard. Like the above ontology-based design process, real-time ontology creation and queries are processed through the interactive user interface and the analytics framework performs a series of processes to visualize this.

On the grounds that structured, unstructured, and ontology BIM analytics are systematical, the collection and analysis of external data, such as social networks, as well as BIM data, must be possible. These are performed with subframeworks for interlinking external data and the existing statistical framework with *R* for statistical analysis, and text mining engines. Earlier in this paper, a system was

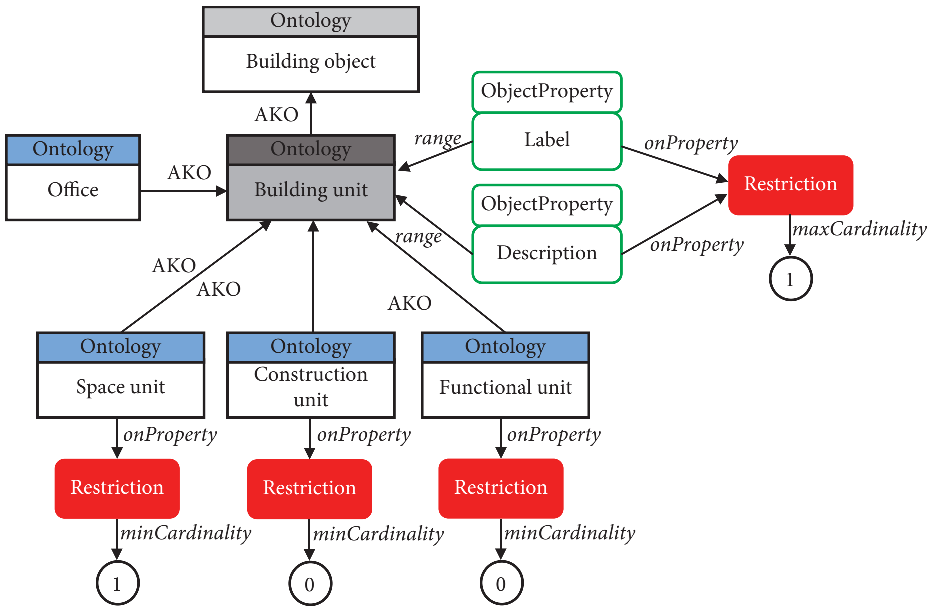


Figure 2: Building units (BUs).

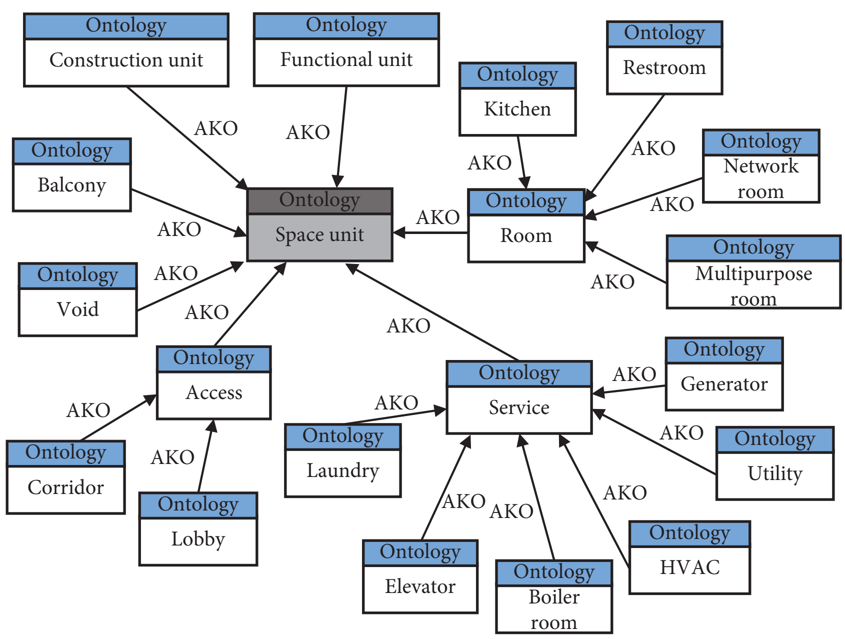


Figure 3: Space units (SUs).

introduced for the real-time processing/analysis of data generated by various sensors in a building. This agrees with the concept of the Internet of Things (IoT) at an expanded scale. In the case of the BIM EAP platform, in-memory computing that can process machine-generated data as the produced data increases in sophistication and size that plays an important role. In-memory computing is especially important for the ontology. Because the query performance on the ontology (i.e., quality and speed of query results) depends on the repository itself, storage, processing, and analysis in the main memory needs to be enabled to maximize the performance.

4.2. Modeling Ontologies. The RDF triples in X3D have identified advantages and limitations to integrate and embed representation. This immediately raised a need to come up with a new way to integrate appropriate XML formats seamlessly, as shown in Figure 8.

In order to describe one domain, it is necessary to use different representation languages to express different aspects of the whole enterprise correctly. X3D, for instance, has a comprehensive set of representing 2D and 3D graphical entities and the acyclic graph structure to visualize complex scenes. Since X3D is a general-purpose graphic representation language, it lacks the ability to represent

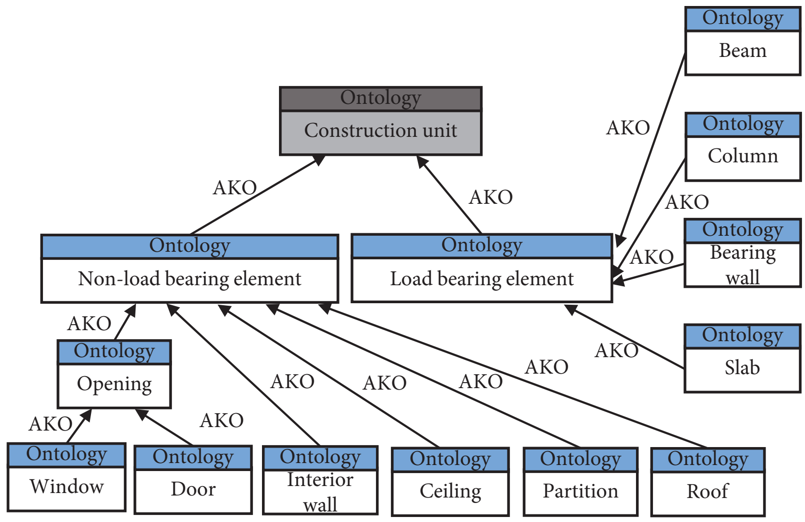


Figure 4: Construction units (CUs).

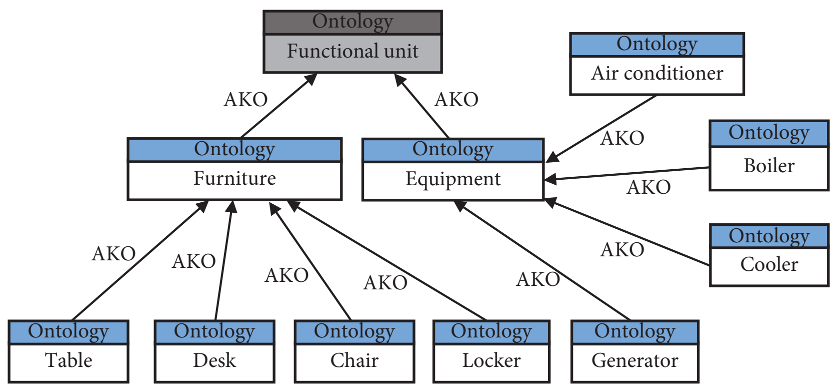


Figure 5: Functional units (FUs).

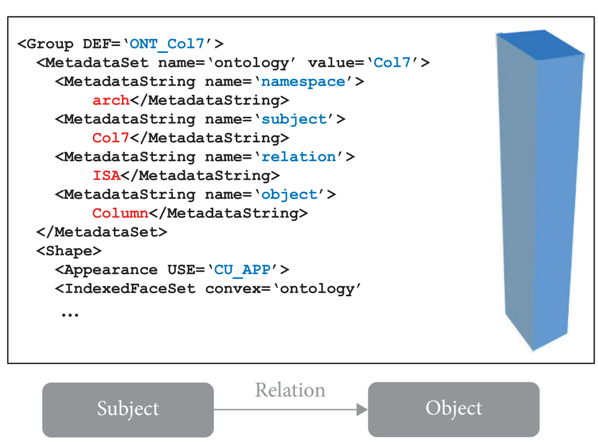


Figure 6: Ontology-based design process model and design expressed by an ontology and RDF triple based on the graph model in [22, 23].

domain ontologies. The IFC has captured sufficient domain knowledge to represent a building as a collection of discrete classes. IFC also supports the XML format [24, 25].

X3D is a successor of Virtual Reality Modeling Language (VRML) that was invented and used in the late 1990s. VRML already has a rich set of representing graphical entities and their interactions through the event model. While rewriting X3D specifications, the Web3D consortium incorporates emerging software technologies, such as distributed networking, physical simulation, geospatial positioning,

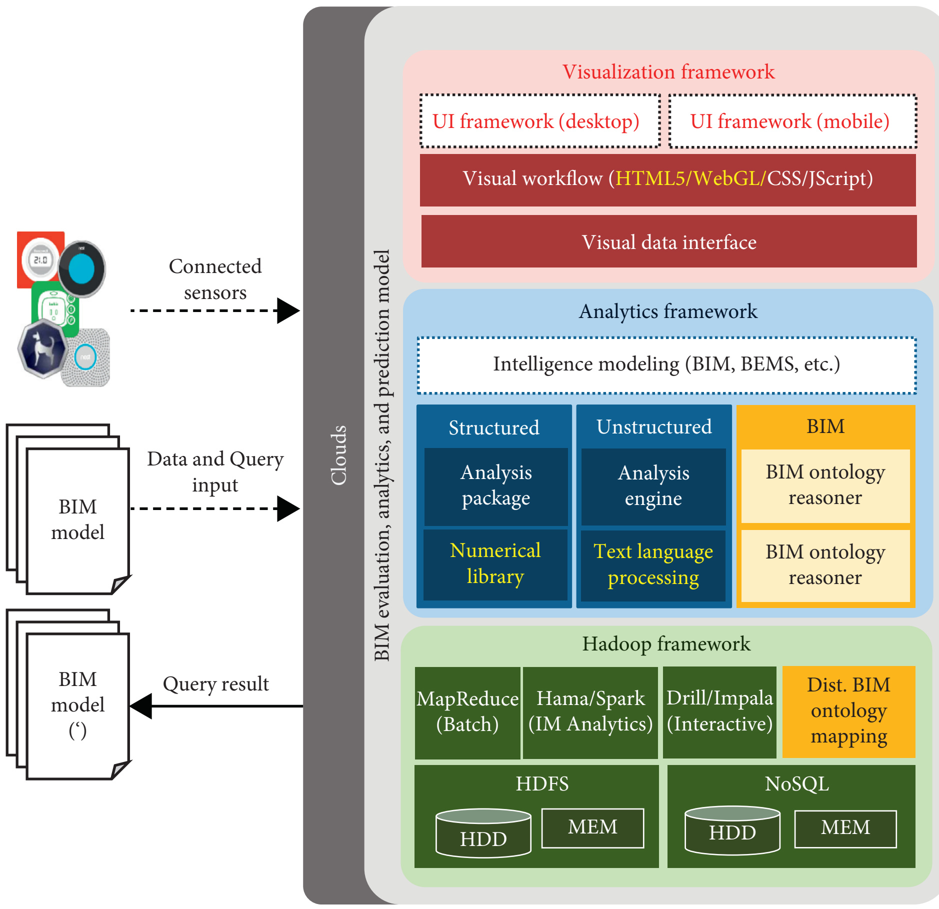


Figure 7: BIM evaluation, analytics, and prediction (EAP) framework and platform.

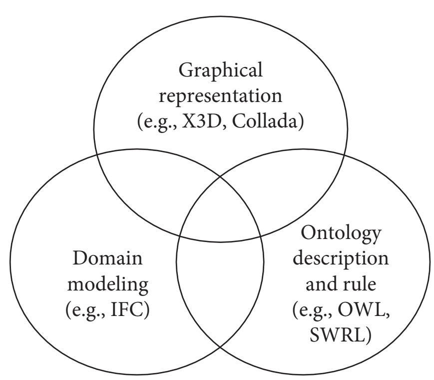


Figure 8: Integration of the XML representations.

programmable shaders, and particle systems by differing corresponding profiles. We used X3D as a vehicle that can accommodate ontological information. The approach that we used was to disassemble the RDF triples into individual components, as shown in Figure 9 (see bold text).

Nonetheless, its XML format merely is an XML version of IFC and still uses a file-based exchange paradigm. The languages that are dedicated to describing ontologies and reasoners (e.g., OWL and Semantic Web Rule Language (SWRL)) have been recently used among so-called knowledge engineers. Although professionals in the AEC industry are design knowledge creators, they are regarded apart from their important roles [26].

4.3. A Case Study of the BIM EAP Platform

4.3.1. Description. The hypothetical case study in Figure 10 is provided to elucidate the function and process of the BIM EAP platform in a multidisciplinary collaborative design environment: the core and shell design of an office building. We assume that there is a land plot, which has predefined

```
<Group DEF='ONT_win01'>
<MetadataSet name='ontology' value='win01'>
        <MetadataString name='owner' value='Armando Trento' />
        <MetadataString name='namespace' value='arch' />
        <MetadataSet name='relation' value='win01'>
                <MetadataString name='subject' value='win01' />
                <MetadataString name='predicate' value='ISA' />
                <MetadataString name='object' value='window' />
        </MetadataSet>
              <MetadataString name='timestamp' value='Sat Apr 12 23:17:02 UTC 2008' />
        </MetadataSet>
        <Shape>
              <Appearance USE='FrontColor_APP'/><IndexedLineSet coordIndex='
                       0 1 -1
                '>
                <Coordinate
              point='
                       508.5285 0.0000 120.0000
                       508.5285 -9.9981 120.0000
                '/>
        </IndexedLineSet>
        </Shape>
         ...
```

Figure 9: A snapshot of X3D.

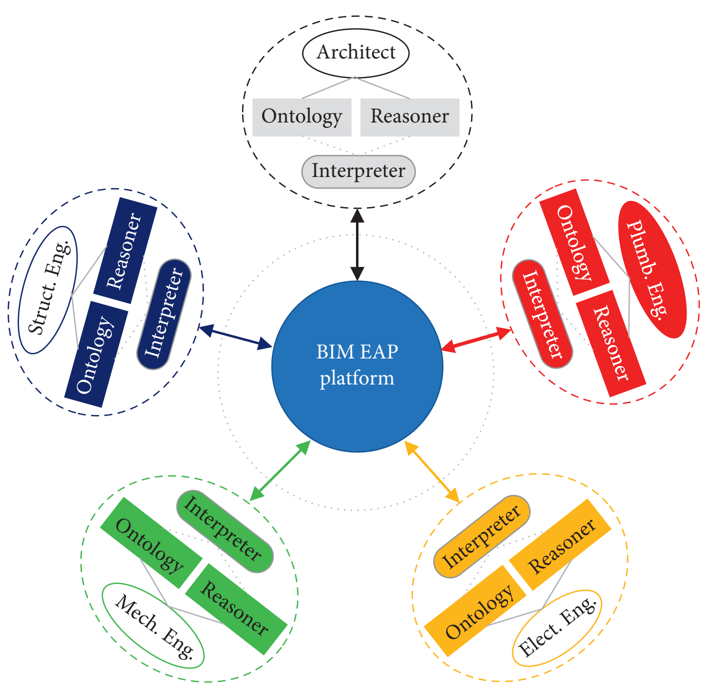


Figure 10: A hypothetical setting for the office building project.

environmental settings (e.g., road and green space) and constraints (e.g., stories), where different experts will collaborate to design an office. The office project has a group of participants, including an architect, structural engineer, mechanical engineer, electrical engineer, and plumbing engineer.

First, the owner needs to specify his/her requirements, which will be shared among all the participants. The architect interprets the owner's requirements and intentions and then generates schematic designs that roughly meet those. At this stage, the role of the architect would be a consultant who helps the owner solidify his/her needs. After the owner is satisfied with the proposed design, the architect begins developing their design. In the course of the design, the architect may encounter several issues that she/he has to resolve, in collaboration with the other participants. In a similar way, the other participants may have similar conflicts that need to be resolved.

Since they have different knowledge, representation, and discipline-specific tools, the participants are subjected to interpret the input data in their own way. In this case study, we are focused on the information flow between the participants: what information is transmitted and how each BIM interpreter interacts with another on behalf of its owner.

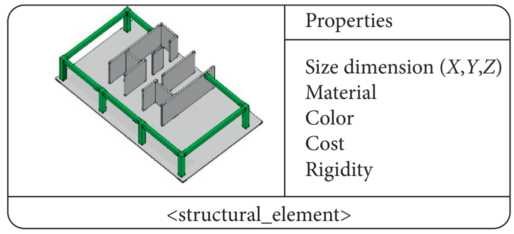


Figure 11: A structural element with a new ontology.

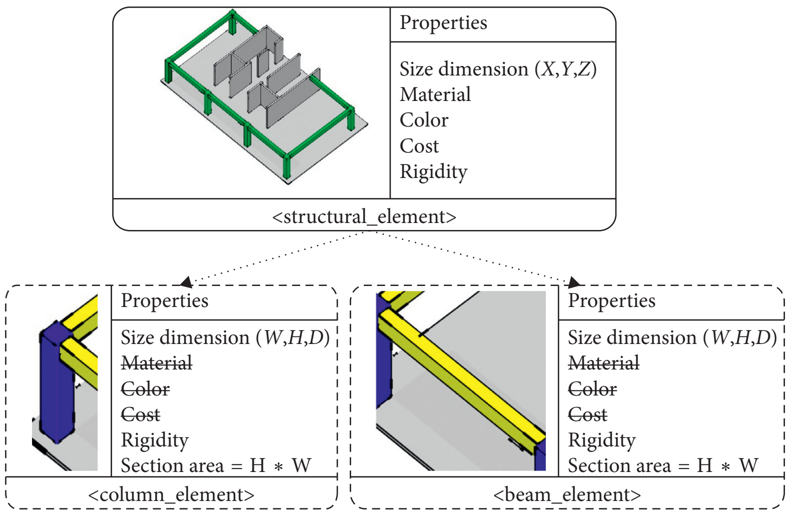


Figure 12: Enriched representation by the structural engineer of the BIM interpreter.

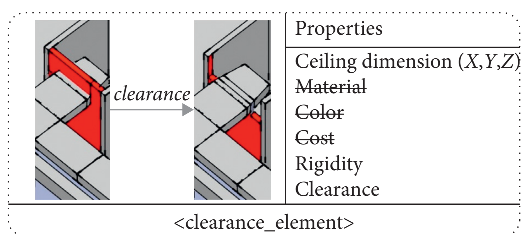


Figure 13: Enriched representation by the MEP engineer of the BIM interpreter.

4.3.2. Assumption. The following assumptions were made for this study. Each participant deals with one aspect of a design. Each application has its own data model, which cannot be directly read by other applications. All data have been written in XML, which can be processed by all the participants. All of the applications can translate the published data into their own data model.

4.3.3. Participants in Collaborative Design Process. The architect is in charge of creating a schematic design considering project guidelines and any particular design criteria specified by the owner. Since the architect does not know the technical details at this point, such as the width and height of columns, the depth of a beam, she/he may develop assumptions from previous experience and knowledge. Before creating drawings, she/he starts by defining her/his ontologies. Although she/he can reuse some ontologies independent of a specific project (e.g., individual products including doors, windows), she/he has to define particular ontologies, if necessary.

For example, she/he draws a box with dimensions (geometric information) and properties (nongeometric information), which are dependent on a specific project. Then, by defining it as a "structural element," she/he can build a new ontology (Figure 11). In this case study, a 3D model is created as a common denominator and her/his BIM interpreter will publish it in XML to the public workspace.

In order to design the structure, the structural engineer needs the architect's model, as well as structural codes and standards. Since the input does not have information on structural analysis, the structural engineer's BIM interpreter will rebuild the model based on her/his own ontologies. For example, when the structural engineer's BIM interpreter receives the architect's schematic model, it tries to differentiate the model to generate proper representation for

Table 2: The hypothetical case study of the collaborative design process in the BIM EAP Platform.

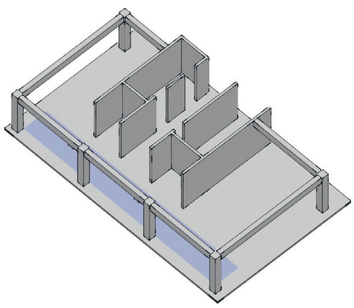
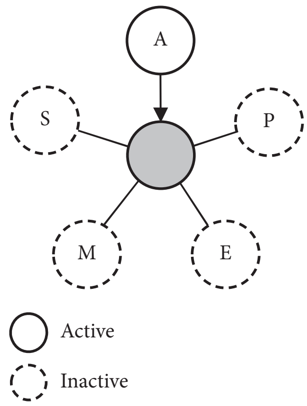
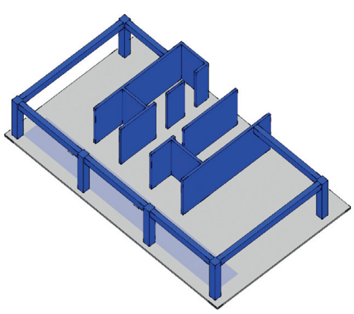
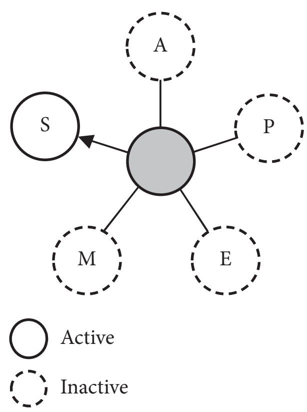
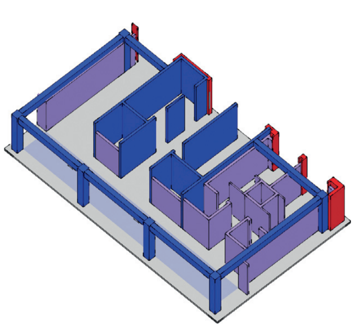
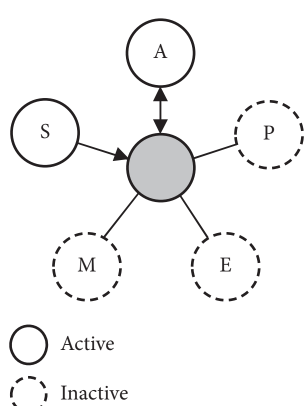
Design processes	Operations of collaborative interactions in X3D
 	Based on the owner's requirement and design criteria, the architect designs the office building using a particular application (e.g., AutoCAD), as well as prior experience/knowledge/ontology and reasoner in her/his private workspace (as we assumed, the model shows a partial plan including the core). The architect creates the geometry using project-independent products, as well as project-dependent ontologies (e.g., <structural_element>). After achieving a certain level of design development, she/he wants the structural engineer to review the design. The architect of the BIM interpreter translates the design created in the application into XML documents and publishes it. The published data will include 3D geometric information and XML tags and ontologies connected to its private data model. As additional information, the published data has the following information: (i) Who: the architect (ii) When: creation date (iii) What: geometry (iv) How: XML/ontology (v) Why: the owner's requirement and design criteria
 	The structural engineer's task is to verify the architect's design in terms of structural buildability. In order for the structural engineer to design the structure of the building, she/he needs the architect's model and structural codes and standards. The BIM interpreter retrieves the latest version of the design. Although it can process the design, the BIM interpreter is missing some information such as "beam" and "column." Therefore, the BIM interpreter begins breaking the architectural model into structural pieces (e.g., horizontal and vertical elements) using the incorporated knowledge base, ontologies, and reasoner tools. Then, it translates the model into the structural engineer's own model to review whether the elements are properly dimensioned and positioned. If she/he finds something that needs to be modified, then the structural engineer redesigns the structure and provides justification. When the structural design is ready, the BIM interpreter gathers necessary information (e.g., 3D geometric data, properties) and publishes the design with XML tags and ontologies.
 	When the structural engineer publishes the design, the published data includes the following information: (i) Who: the structural engineer (ii) When: modification date (iii) What: geometry (iv) How: XML/ontology (v) Why: structural buildability When the architect's BIM interpreter receives the structural design and represents it with architectural ontology, the architect may decide whether she/he accepts the proposed design. Although it would be unrealistic in reality, let us assume that the design of the structure initially conformed to the architect's requirements thanks to the BIM interpreter communication. Constraints for the architect's design development are immediately available. Based on this information, the architect may begin designing interior walls and exterior compartments. For the interior walls, she/he allows further modification (e.g., tolerance) because she/he has prior experience with the MEP engineers.

Table 2: Continued.

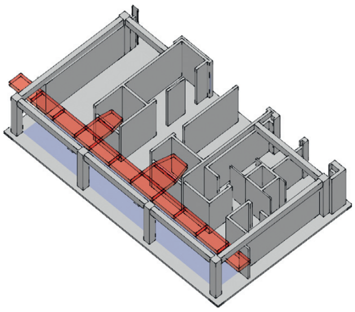
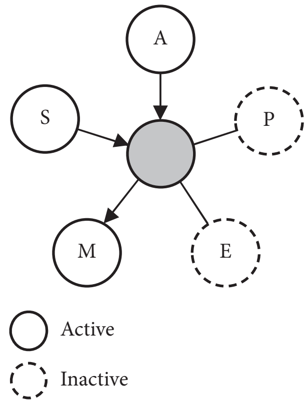
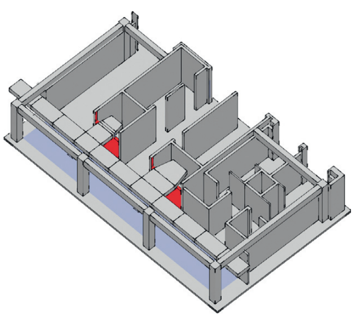
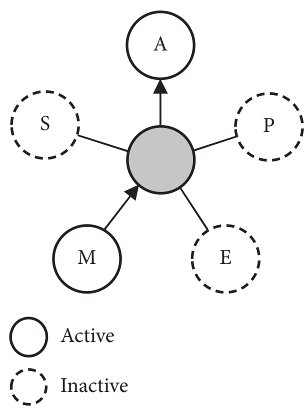
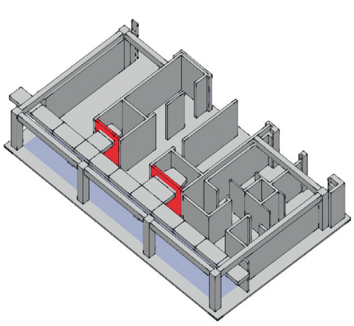
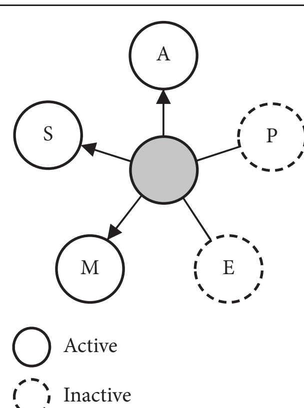
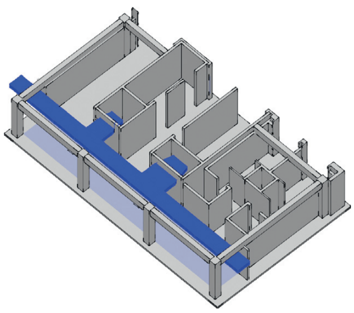
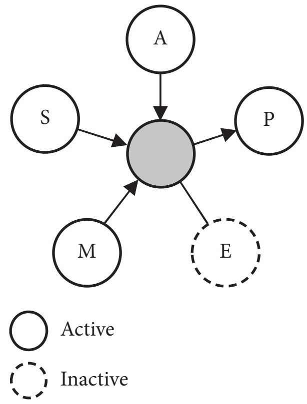
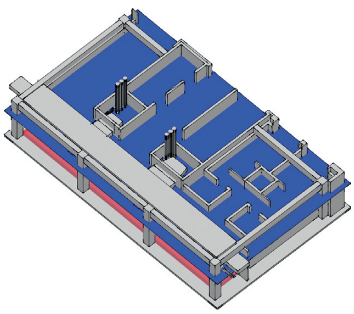
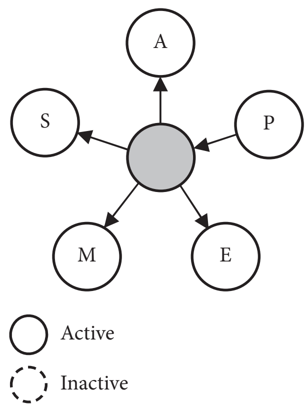
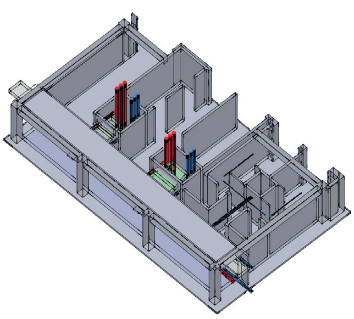
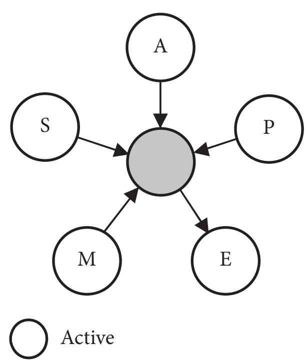
<table>
<tr><th>Design processes</th><th colspan="2">Operations of collaborative interactions in X3D</th></tr>
<tr><td></td><td>
</td><td>The mechanical engineer's primary concern is installing the ducts due to their size and inflexibility. In most cases, architectural and structural designs act as constraints for designing ducts and pipes. The size, material, and shape of the ducts and fittings along with the size, material, and connection type of the pipes and the elevation of air terminals should be based on the input data, as well as specifications.
As mentioned earlier, the first task of the interpreter is to find available spaces where the ducts can fit using the provided knowledge bases, ontologies, and reasoner tools, and then illustrate them, as suggested in the view on the left.</td></tr>
<tr><td></td><td>
</td><td>The mechanical engineer tries to fit the ducts in the available space suggested by the BIM interpreter. However, it appears that fitting in the space requires a special design (e.g., connection type) that usually leads to cost increase. Then, she/he tries to find out whether modification of the design would be allowed. First, she/he designs the duct and puts it in the same space.
As soon as she/he tries to put it there, she/he can recognize there is physical interference, as shown on the left. Then, the BIM interpreter displays who is in charge of the proposed design and semantic information (e.g., load-bearing or nonload-bearing wall). Let us assume that the interfering walls turn out to be nonload-bearing. Then, the mechanical engineer decides to modify them with additional information (e.g., explanation on his proposed action). The BIM interpreter will publish the proposed design with the following information:
(i) Who: the mechanical engineer
(ii) When: modification date
(iii) What: geometry
(iv) How: XML/ontology
(v) Why: physical interference</td></tr>
<tr><td></td><td>
</td><td>After the BIM interpreter of the mechanical engineer publishes the proposed design, the architect's BIM interpreter retrieves and processes it. Consider the case that the proposed design is within the range of the tolerance specified by the architect. Still, the BIM interpreter lets the architect know that there is a modification proposed by the mechanical engineer. After getting the architect's confirmation, her/his BIM interpreter publishes the accepted design to remain consistent. Likewise, the architect's published data will be retrieved and processed by the BIM interpreter for the structural engineer and the mechanical engineer.</td></tr>
</table>

Table 2: Continued.

Design processes	Operations of collaborative interactions in X3D	
		The situation for the plumbing engineer is more challenging than that of the mechanical engineer. The main constraints imposed on her/him would be the architectural and structural designs, as well as the mechanical designer's ducts. Therefore, her/his primary task is to determine whether there is enough space to accommodate pipes. When the BIM interpreter retrieves all the published data, which were contributed by the architect, the structural engineer, and the mechanical engineer, it begins analyzing geometries to find available spaces. Then, it suggests the spaces surrounded by the beams/columns (the structural engineer) and the ducts (the mechanical engineer) including clearance confined by the ceiling (the architect). If she/he could accommodate all pipes in the suggested spaces, the plumbing engineer could safely let her/his BIM interpreter to publish the design.
		Once she/he is done with the pipe layout, the plumbing engineer lets the BIM interpreter publish the design. Then, the other participants of the BIM interpreter will be notified with the following information: (i) Who: the plumbing engineer (ii) When: creation date (iii) What: geometry (iv) How: XML/ontology
		The electrical engineer's situation is the most challenging because their designs will all constrain her/his design.

structural analysis (Figure 12). Since the architect's model tagged "structural element," the structural engineer's BIM interprets it as a composite model consisting of a "column" and "beam" using its own ontology and reasoner. In addition to that, the BIM interpreter ignores material, color, and cost which are not pertinent to structural calculations. For the same reason, it adds a "Section Area" property to the model. Based on this information, the structural engineer conducts analysis using her/his own disciplinary tools.

The mechanical systems included here are HVAC supply ducts. The plumbing engineer's task is to route sanitary waste, and the electrical engineer has to deal with cable trays and conduits. The MEP (mechanical, electrical, and plumbing) engineer's primary concern is whether the corridor ceiling spaces were deep and wide enough to contain the necessary MEP systems. Therefore, the architect's and structural engineer's design criteria usually act as constraints. The BIM interpreter connected to the MEP engineers will deduce clearance and available spaces from the input geometry (Figure 13). Then, the BIM interpreter will ignore material, color, cost, and rigidity and add "Clearance" to the model. The electrical engineer's task is even more complicated because her/his design has to comply with constraints imposed by the architectural design, clearances required by code and specifications, along with the layout design of other MEP systems.

The design processes (Table 2) illustrated in this case study will describe only a part of the rather lengthy and iterative design development process. The design processes envision that each participant uses their own knowledge and representation methods and that their intelligent BIM interpreters retrieve other participants' knowledge in order to construe their own representations. It would explain that an object can be understood from within more than one domain at the same time, thereby, raising the possibility of multiple interpretations.

5. Conclusion and Future Directions

This paper describes the usability of the existing BIM and introduces an ontology to enable user-oriented object definition and operation with example cases. The concept and technology of big data and the BIM EAP platform for utilizing big data are presented to cope with the explosive increase in data of large-scale projects. These are important technological elements for establishing a model to assess and analyze BIM data, which will continue to increase and has emerged as a main topic for the entire AEC industry. Therefore, the early construction of the BIM EAP platform is expected to be helpful for establishing related policies in the future and maximizing the utilization value of BIM data. Support is also required for the construction of large-scale BIM ontologies and reasoners composed of OWL/RDF as key technical elements, as well as continuous research and development of technology for collection, processing, analysis, and case studies for actual application.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2016R1D1A1B01012688).

References

[1] S. Azhar, "Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry," *ASCE Journal of Leadership and Management in Engineering*, vol. 11, no. 3, pp. 241–252, 2011.

[2] B. Gilligan and J. Kunz, *VDC Use in 2007: Significant Value, Dramatic Growth, and Apparent Business Opportunity, TR171, 36, Center for Integrated Facility Engineering*, Stanford University, Stanford, CA, USA, 2007.

[3] H. W. Rittel and M. M. Melvin, "Dilemmas in a general theory of planning," *Policy Sciences*, vol. 4, no. 2, pp. 155–169, 1973.

[4] R. Kohavi, N. Rothleder, and E. Simoudis, "Emerging trends in business analytics," *Communications of the ACM*, vol. 45, no. 8, pp. 45–48, 2002.

[5] J. Evans, "Business analytics: the next frontier for decision sciences," *Decision Line*, vol. 43, no. 2, pp. 4–6, 2012.

[6] N. Piedra, J. Chicaiza, J. Lopez-Vargas, and E. T. Caro, "Guidelines to producing structured interoperable data from Open Access Repositories," in *Proceedings of Frontiers in Education Conference (FIE)*, pp. 1–9, IEEE, Erie, PA, USA, October 2016.

[7] N. Piedra, J. Chicaiza, J. Lopez-Vargas, and E. T. Caro, "A rating system that open-data repositories must satisfy to be considered OER: reusing open data resources in teaching," in *Proceedings of Global Engineering Education Conference (EDUCON)*, pp. 1768–1777, IEEE, Athens, Greece, April 2017.

[8] J. Beetz, J. P. Van Leeuwen, and B. De Vries, "An ontology web language notation of the industry foundation classes," in *Proceedings of the 22nd CIB W78 Conference on Information Technology in Construction*, pp. 193–198, Westin Bellevue, Dresden, Germany, 2005.

[9] L. Zhang and R. R. Issa, "Development of IFC-based construction industry ontology for information retrieval from IFC models," *EG-ICE Workshop*, University of Twente, The Netherlands, 2011.

[10] P. Pauwels, S. Zhang, and Y. C. Lee, "Semantic web technologies in AEC industry: a literature overview," *Automation in Construction*, vol. 73, pp. 145–165, 2017.

[11] J. Manyika, M. Chui, B. Brown et al., *Big Data: The Next Frontier for Innovation, Competition, and Productivity*, McKinsey Global Institute, New York City, NY, USA, 2011.

[12] R. Kumar, B. B. Parashar, S. Gupta, Y. Sharma, and N. Gupta, "Apache Hadoop, NoSQL and NewSQL solutions of big data," *International Journal of Advance Foundation and Research in Science & Engineering (IJAFRSE)*, vol. 1, no. 6, pp. 28–36, 2014.

[13] A. Khan and K. Hornbæk, "Big data from the built environment," in *Proceedings of the 2nd International Workshop on Research in the Large*, Beijing, China, pp. 29–32, ACM, New York, NY, USA, 2011.

[14] Y. Jiao, Y. Wang, S. Zhang, Y. Li, B. Yang, and L. Yuan, "A cloud approach to unified lifecycle data management in architecture, engineering, construction and facilities management: integrating BIMs and SNS," *Advanced Engineering Informatics*, vol. 27, no. 2, pp. 173–188, 2013.

[15] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley & Sons, Hoboken, NJ, USA, 2011.

[16] http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html, 2018.

[17] https://www.w3.org/community/lbd, 2018.

[18] S. Jupp, J. Malone, J. Bolleman et al., "The EBI RDF platform: linked open data for the life sciences," *Bioinformatics*, vol. 30, no. 9, pp. 1338-1339, 2014.

[19] https://www.w3.org/RDF, 2018.

[20] https://www.w3.org/OWL, 2018.

[21] A. X. Sanchez, K. D. Hampson, and S. Vaux, *Delivering Value with BIM: A whole-of-life approach*, Routledge, Abingdon, UK, 2016.

[22] J. Lee and Y. Jeong, "User-centric knowledge representations based on ontology for AEC design collaboration," *Computer-Aided Design*, vol. 44, no. 8, pp. 735–748, 2012.

[23] J. J. Carroll and P. Stickler, *RDF Triples in XML*, in *Proceedings of the 13th international World Wide Web conference on*

Alternate track papers & posters, ACM , New York, NY, USA, pp. 412–413, 2004.
[24] http://www.buildingsmart-tech.org/specifications/ifcxml-releases, 2018.
[25] http://www.web3d.org, 2018.
[26] https://www.w3.org/Submission/SWRL, 2018.