Advances in Civil Engineering

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Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 1901201, 13 pages
https://doi.org/10.1155/2022/1901201

Research Article

BIM Model Management for BIM-Based Facility Management in Buildings

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Received 27 August 2021; Accepted 18 March 2022; Published 11 April 2022

Academic Editor: Alberto Sanchez

Building information modeling (BIM) has recently gained popularity in the architecture, engineering, and construction industry. Specifically, BIM has been applied in facilities management (FM). However, FM-integrated BIM and MM-integrated BIM are likely to fail when BIM-FM models are not effectively updated or maintained. Thus, it is critical to focus on the management of BIM-FM models during the operation stage of buildings. While several researchers have examined BIM applications and system developments in the context of FM, there is a dearth of research on BIM management, particularly in the operation stage of sustainable buildings. Thus, an approach for BIM-FM models management is herein proposed for building projects. A BIM-FM models management (BFMM) system for owners during the operation stage was developed to ensure effective implementation for the management of BIM-FM models. Using a building in Taiwan as a case study, this study discussed and evaluated the effectiveness of the proposed BFMM system. The results reveal that the BFMM system significantly increases the efficiency of BIM-FM model management. The results of this study can provide a useful reference for those interested in adopting BIM to manage building project facilities. This study concludes by presenting the advantages and limitations of BIM-FM models as well as suggestions for future applications.

1. Introduction

Building information modeling (BIM) includes geometry, spatial relationships, geographic information systems, and quantity of various building components. BIM can be applied in determining the life cycle of building or construction projects, including the design stage, construction stage, and operation stage. Particularly, BIM is being widely adopted in various building projects. One of the main features of BIM is 3D illustration, which allows the owners to use BIM for facility management (FM) during the operation stage from design and construction stages [1]. Therefore, management of BIM models for FM (BIM-FM models) is a very important core factor. Although BIM-FM models are available for FM usage during the operation stage, the final implementation result of BIM-FM applications is not successful. When BIM-FM models are incorrect and not properly managed, BIM applications and implementation cannot be executed well and the FM result will have errors [2]. Furthermore, BIM-FM models will lose their credibility among FM engineers. Therefore, suitable management of BIM-FM models will affect the effectiveness of BIM implementation for FM during the project operation stage [3]. The BIM-FM management process includes the development of new BIM-FM models, submission of models for confirmation, modification of BIM-FM models if necessary, and confirmation of modified BIM models prior to delivery to facility owners for use in FM.

A key step in the management of BIM-FM models is updating and modifying BIM-FM models according to process requirements. Failure to properly update and correct BIM-FM models results in the use of outdated or inaccurate versions, leading to unsuccessful implementation of BIM-FM management during the operation stage [4]. Currently, many practical problems have been found to cause unsuccessful FM-based BIM implementation. According to a survey of Taiwanese project owners [5], the existing problems for the practical management of BIM-FM models are majorly the following: (1) BIM-FM models are not frequently updated; (2) BIM-FM models do not include the required nongeometrical information for use in FM; (3) there is lack of responsible staff to handle FM-based BIM management tasks in the owner-operator FM organization; (4) there is lack of facility information linked with BIM-FM models; and (5) few suitable platforms exist to assist in the management of BIM-FM models.

Although many previous BIM studies are related to FM, few studies have been conducted on the effective management of the BIM model update mechanism during the operation stage. To improve the owner's ability to control BIM-FM models more effectively, this study proposes a BIM-FM model for the FM management mechanism and develops a BIM-FM model management platform. Previous literature rarely discussed the BIM-FM models for the FM mechanism. Without suitable BIM-FM models for the FM management mechanism, BIM will encounter many difficulties during the implementation of the use of BIM for FM. At present, there are numerous BIM systems and software developed for FM by researchers and industry. However, few systems are developed which are suitable for the management of the BIM-FM model for FM. To improve the effective implementation of BIM for FM, this study proposes a BIM management approach and develops a system for the management of BIM-FM models for building projects. The main objectives of this study are to (1) propose a management approach for BIM-FM models of building projects, (2) develop a web-based system for the management of BIM-FM models integrated with the proposed approach, (3) apply this system to a case study in Taiwan to confirm the effectiveness of the proposed approach and the system usage by managers of BIM-FM models, and (4) identify the advantages and limitations of applying the proposed management approach and system based on the results of the case study.

The paper begins with literature review. Then, an overview of the proposed method is described, and the development of the prototype system is explained in detail. A case study with an actual building project for FM implementation integrated with BIM is used to verify the prototype system and validate the proposed method. The proposed method and system are compared with traditional FM methods. Then, the results and limitations are discussed and the conclusions are summarized.

2. Background

The construction industry commonly uses BIM from the design to the operation phases of a building's lifecycle [6]. As a new approach to the design, construction, and management of facilities, BIM promotes the exchange and interoperability of information in digital format during the building process. BIM and its associated processes are being applied to produce and analyze building models [1, 7]. FM departments employ BIM to manage coordinated, consistent, and computable building information [8, 9]. In particular, the approach helps eliminate tedious data entry processes that are prone to errors and information loss during a project's lifecycle [1, 10]. BIM-integrated FM provides faster data access and helps improve the process of locating various facility elements through its user-friendly 3D interface, thus increasing the efficiency of work order executions [11–16].

Numerous studies have investigated the application of BIM to FM during the operations phase. Becerik-Gerber et al. [17] explored how BIM can be a beneficial platform for supplementing FM practices. Pishdad-Bozorgi et al. [18] proposed a body of knowledge by first defining and examining pilot implementation of FM-enabled BIM and then discussing the challenges encountered. Gao and Pishdad-Bozorgi [15] provided potential solutions for BIM-based FM application challenges and specific recommendations for future research related to BIM-based FM. Kamal et al. [19] proposed an integrated BIM-based framework for effective facility maintenance management.

BIM-based system development has been extensively studied in the past. Some studies have focused on the integration of Industry Foundation Classes (IFC) and BIM for FM [20–24]. Furthermore, numerous studies have focused on BIM integrated with point clouds for FM of existing buildings [16, 25]. Many studies have presented research on BIM-based information system development for FM. Wetzel and Thabet [14] proposed the BIM-based framework to support safe maintenance and repair practices for FM. Suprabhas and Dib [26] developed system integrated sensor data collected using a wireless sensor network via a virtual model of the building. Patacas et al. [27] developed a framework and a prototype system integrated BIM and Common Data Environment (CDE) using open standards for FM. Lavy et al. [28] investigated the effects of using BIM and construction operations building information exchange (COBie) data for FM. Pärna and Edwards [29] presented application programming interface (API) for BIM-FM integration. Pan and Chen [30] developed a BIM-based facility repair platform integrated with QR code for FM. Behlul Kula and Esin Ergen [31] discussed real-life case study implementation of a BIM-FM platform at an international airport project. Mohamed et al. [32] integrated the as-is information BIM and semantic web technology to ensure versatile formalization and management of existing building as-is information. Hsieh et al. [33] proposed a semiautomated FM system to formalize the reuse process of BIM service in semiconductor fabrication plants. Li et al. [34] developed a BIM-enabled BLM system for property owners using a semicustom approach.

Although there are many advantages integrated with various applications of BIM to FM, BIM application in the context of FM can be difficult and even unsuccessful if the BIM-FM models are not accurate or updated [11, 13, 17, 18]. Although previous researchers have focused on different BIM applications and system developments for FM, few have focused on the management of BIM-FM models during the operation stage. Therefore, the present study proposes and develops a system to improve the effectiveness of the management of BIM-FM models in the operation stage of sustainable buildings.

3. Research Method

In this study, all practical problems associated with the management of BIM-FM models are identified and summarized on the basis of the results of interviews. From this, an approach is proposed to solve these practical problems and a system is developed according to the identified requirements. Finally, a case study is applied and discussed to evaluate the effectiveness of the proposed system.

In this study, ten interviews with BIM professionals (with over 12 years' experience in BIM-FM) were conducted to (1) explore the current state of the practical management of BIM-FM models and (2) identify areas that need further development. The interviews were semistructured, with the same six open-ended questions asked to each interviewee to capture their understanding of the practical management of BIM-FM models. The six interview questions are as follows:

(1) What is your background?

(2) What is your role in your BIM-FM project or organization?

(3) What are the most important considerations for the successful implementation of the practical management of BIM-FM models?

(4) What are the most important requirements for the successful implementation of the practical management of BIM-FM models?

(5) What are the most important suggestions for the successful implementation of the practical management of BIM-FM models?

(6) What are the helpful system functions that would assist in the implementation of the practical management of BIM-FM models?

The interview results were summarized to identify the important requirements and required system functions to be recognized, and, based on these results, the proposed approach and system development process will be developed. Table 1 summarizes the interview responses.

During the operation stage, when the BIM-FM model needs to be added, updated, or revised, an audit mechanism is required. Although a suitable platform is provided, the implementation of the audit mechanism requires considerable manpower and time, which will lead to considerable difficulties in practical implementation.

It is necessary and essential to provide a correct as-built model or complete inspection of the as-built model for BIM management for BIM-based facility management, without which subsequent revisions and updates of the BIM-FM model will be more labor- and time-intensive. Currently, Taiwan's large-scale engineering contracts require the delivery and verification of the completed BIM model, which would take 4–6 months (including inspection and correction time). The delivery and verification of the completed BIM model affect the performance of the BIM model management for BIM-based facility management.

At present, many large-scale projects in Taiwan have planned to apply BIM to the entire life cycle, especially in the operation stage. Currently, there are few successful cases of BIM for FM, majorly because of the following problems. First, although the construction general contractor submits the completed BIM model according to contract requirements, the owner does not have a comprehensive plan to effectively convert the completed BIM model into a BIM-FM model. Second, the completed BIM model is directly converted to a BIM-FM model, including the nonessential information present in it. Finally, after maintenance and management, the BIM-FM model is either not updated or updated with no confirmation mechanism.

In general, the model built by the new version of the BIM software cannot be opened by the older version. If the FM department continuously updates the BIM software but there is no high usage during the operation process, then it is an unnecessary expenditure of the limited annual budget allocated for the FM department for BIM management. This eventually results in the FM department not planning to purchase or renew new version of the BIM software. After a few years, the old version of BIM software becomes obsolete for application in BIM model development or modification. Therefore, it is necessary and important to consider software cost for purchasing or renewing new BIM software versions. It is a serious problem in the way of successful implementation of BIM model management for BIM-based facility management.

Currently, there are two different methods for facility owners to handle BIM applications for FM. One method relies on the owner-operator FM organization, while the other relies on FM service providers (BIM outsourcing services) or BIM outsourcing companies. The results of the present study are only suitable for the management of BIM-FM models by owner-operator FM organizations.

This study proposes the principle management components of BIM-FM models, including the development of the new BIM-FM model, submission of the model for confirmation, modification of existing BIM-FM models, submission of the modified model for confirmation, and confirmation of BIM models prior to delivery for application in FM.

Furthermore, all related important information should be recorded and tracked for the management of the BIM-FM models during the modeling process (such as update time, the individual who updated the model, and which content is updated). Finally, the confirmed new or modified BIM models will be delivered to a BIM-based FM system for FM work.

Senior management support is very important for BIM model management for BIM-based facility management. Although BIM has the effect of 3D rendering, the relevant personnel who are already familiar with the FM work have not fully accepted BIM technology. One of the main reasons is that they prefer using the current method without changing the mode for FM work. Therefore, only senior management support and encouragement can effectively implement BIM model management.

FM-based BIM includes the management of geometric and nongeometric information. The requirements for

Table 1: Summaries of the responses from the interviews.

No.	Responses
1	Interviewed by BIM manager: It is very important for owners to know which FM information needs to be tracked and managed in advance. There are many BIM models to be developed during the operation stage. Without careful consideration and planning, there will be serious time consuming problems in practice.
2	Interviewed by BIM manager: It takes lot of time to track and manage updating and revised BIM-FM models from different participants during the process. I suggest that it will be helpful and effective when the newest result of BIM-FM model modification and development can be traced and managed through the online system. It will be useful and helpful for responsible managers.
3	Interviewed by FM/BIM engineer: In our organization, some of the BIM-FM models were updated and revised many times. Sometimes, I adopted old BIM-FM models for FM. Therefore, it is necessary and helpful to provide the newest BIM-FM models through the centralized storage platform.
4	Interviewed by FM/BIM manager: When a new facility is purchased during the operation stage, the owner-operator FM organization will not be notified to develop the new BIM model for FM. Therefore, it is necessary to provide management mechanisms to develop BIM models for FM if the new facility will be planned to have the integration of FM and BIM.
5	Interviewed by BIM manager: Based on my experience, most nongeometric information in BIM-FM models are blank or have errors. Without suitable and clear employer information requirements and planning, it will be very difficult for the general contractor to enter the required nongeometric information of all BIM-FM models during the project closeout stage.
6	Interviewed by BIM engineer: For the effective implementation for the management of BIM-FM models, it is necessary and helpful to provide a management platform to assist in the development of new BIM-FM models and modifications tasks. Furthermore, there is important information necessary for this to be traced and managed. This information should include the status of the modeling work and finished BIM-FM models for new development or modification.
7	Interviewed by BIM engineer: Usually I need to access the version history and record of changes regarding updating the BIM-FM model. Therefore, it will be useful and effective for me if the system can provide the historical modification records regarding the selected revised BIM-FM model.

nongeometric information vary with different BIM-FM models and must be inspected and confirmed prior to model implementation. However, there are a few functionalities designed for the above objects. Therefore, this study aims to enhance the performance of the management of BIM-FM models. Figure 1 illustrates the proposed concept for the management of BIM-FM models.

Based on the FM requirements, there are five major personnel roles for the management of a BIM-FM model: a general contractor, an equipment supplier, an FM engineer, an FM manager, and a BIM engineer. The FM engineer is responsible for submitting applications and requirements to develop a new or modified BIM model for FM during the operation stage. The FM manager handles and manages performance and practical requirements of all BIM models for FM during the operation stage. The BIM engineer develops a new BIM model or modifies existing BIM models for FM based on requirements from FM engineers or FM managers during the operation stage. The general contractor delivers the final as-built BIM model to the owner for FM at the final stage of a construction project. Finally, the equipment supplier delivers the equipment for FM and provides related equipment information for FM during the construction or operation stage.

To enhance the management of BIM-FM models during the modeling process, four statuses for their control and management are proposed: identification, modification, confirmation, and notification. In the identification status, requirements for the development or modification of a BIM model for FM are proposed. In the modification status, a new BIM model is developed or a BIM model is modified for FM based on the requirements. In the confirmation status, the results of the new BIM model development or BIM model modification for FM based on the requirements are confirmed. Finally, in the notification status, notifications are provided to related personnel about the new BIM model development or BIM model modification for FM.

There are two main sources of BIM-FM models: a model from the completed project and a model generated during the operation stage. When a BIM-FM model requires an addition or update, a mechanism needs to be developed for the BIM-FM model management to confirm the BIM-FM model changes and to inspect the results and then notify the relevant stakeholders. With these different statuses, each BIM-FM model can be managed and tracked for effective management. Figure 2 shows the major components of the management of BIM-FM models for owners.

Based on suggestions from the interviews, the five following forms are proposed for assisting in the management of BIM-FM models: a form for the development of new BIM-FM models, a form for the modification of existing BIM-FM models, a form for the confirmation of BIM-FM models, a summary for all process work for the BIM-FM models, and a summary for all confirmed BIM-FM model works. These forms must be integrated with management processes and shared with related personnel. The proposed management framework for BIM-FM models is shown in Figure 3. The four following different flowcharts are presented for enhancing the management mechanisms of BIM-FM models: a main flowchart for the management of BIM-FM models, a flowchart for the development of new BIM-FM models, a flowchart for the modification of existing BIM-FM models, and a flowchart for the confirmation of BIM-FM models.

Figure 4 shows the flowchart explaining the major workflow for system development for the management of BIM-FM models. The flowchart includes the four main stages in the management of BIM-FM models, namely,

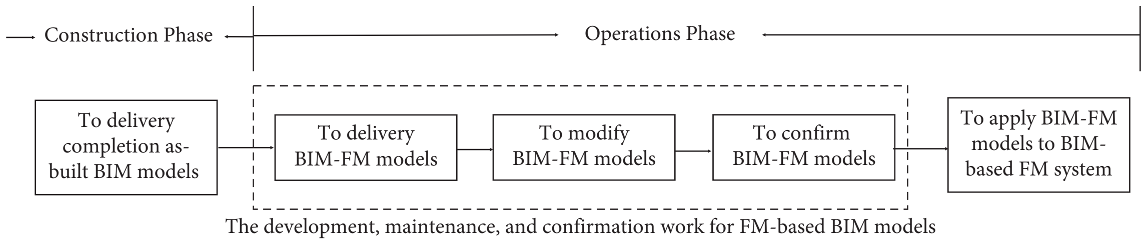

Figure 1: The concept of management of BIM-FM models.

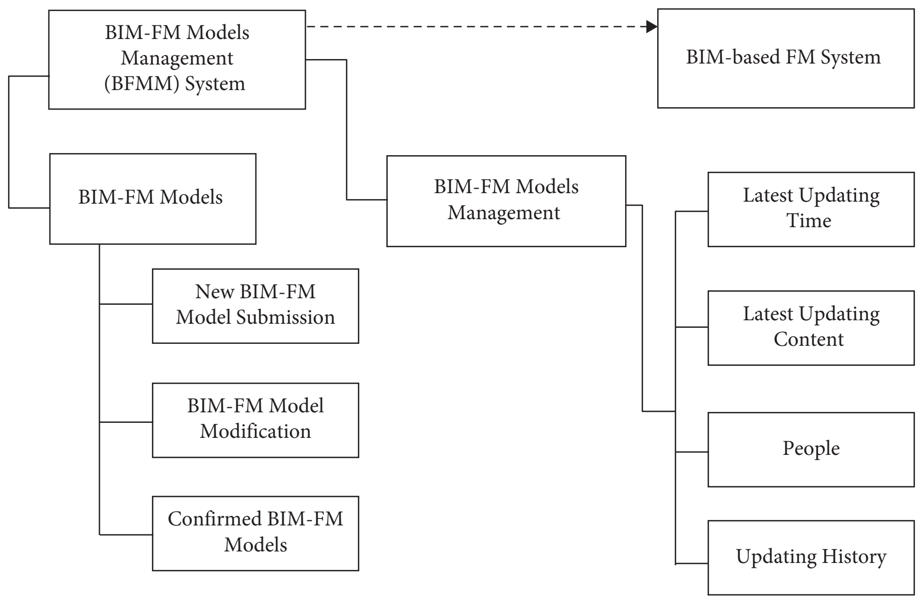

Figure 2: The major components of management of BIM-FM models for owners.

identification, modification, confirmation, and notification statuses. This management process involves new model development, correct confirmation for the final model, and notifying relevant personnel regarding the confirmation. Each stage includes decisions for controlling and managing BIM-FM models. The entire management and control of the workflow are executed through the proposed system, with the BIM-FM models following the management mechanism integrated with relevant personnel and other important information.

4. System Development

To achieve the proposed management mechanism, a BIM-FM model management (BFMM) system is designed and developed based on the identified requirements for the management of BIM-FM models. Furthermore, the major purposes of the BFMM system are to (1) provide an overview of the current state of all BIM-FM models, (2) provide the required checklist of nongeometric information for the BIM-FM model, and (3) show the version history and record changes of the BIM-FM models.

Windows 10 is selected as the operating system for the proposed BFMM system, programmed using the Navisworks API. The portal subsystem of the BFMM system is programmed using Java Server Pages (JSP). All authorized users can access the portal subsystem of the BFMM system through web browsers. The BFMM system comprises interface, access, application, and database layers. The interface layer executes administrative work at the end-user side. The access layer carries out system administration and security. The application layer provides the major functions of the system based on client requests. Finally, the database layer organizes and stores data and information during the system processes. The framework and related modules of the BFMM system are illustrated in Figure 5.

Four modules are designed and developed in the BFMM system. The major functions of the modules are to handle versioning, status selection, result updating, statistic collection, and workflow control for BIM-FM management. This following section will explain the function of each module of the BFMM system.

4.1. BIM-FM Model Editing Module. This module allows users to edit the required content for the development of new BIM-FM models or for modifying existing BIM-FM models. After submission of the BIM-FM model, the required nongeometric information of the BIM-FM model will be inspected. This module lets the FM engineer edit the required description and submit the BIM-FM model. After the request is approved by

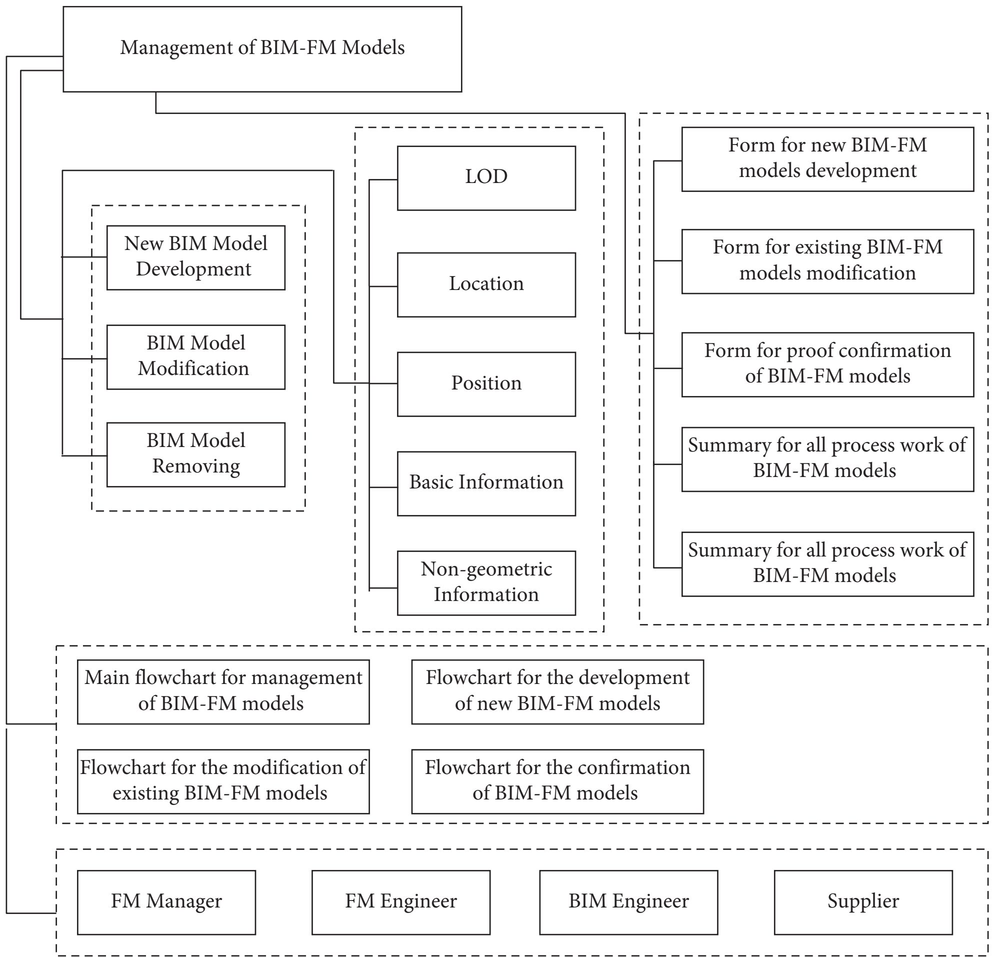

Figure 3: Framework for management of BIM-FM models.

the BIM manager or the FM manager, the process will be recorded and tracked. Furthermore, the module will include the relevant important information (such as 2D location details and related supplemental and requested photos from the BIM-FM models for FM).

4.2. Historical Record Module. This module provides a collection of historical records of all submitted BIM-FM models. In general, it is necessary and important for reference to record previous versions of BIM-FM models. These historical records include the responsible BIM engineer's name, the previous modified version of the BIM-FM model, and previously recorded brief explanations of modifications of the BIM-FM model. This module enhances the complete version history for different versions of BIM-FM models.

4.3. Dashboard Module. This module can display the current result of the BIM-FM models as shown via a dashboard. The major advantage of this module is that a simple bar and pie chart is presented for use in major control management of the BIM-FM models. It is necessary and important for managers to access the current management condition of BIM-FM models through the module.

4.4. Analysis Module. This module can show the analysis and statistical result of BIM-FM models displayed by the dashboard. The major functionality of this module is to illustrate model statistics for management of available BIM-FM models in the project. It is helpful for the relevant personnel to understand the current statistics related to the management of BIM-FM models for advanced decision-making.

Furthermore, the following Revit API and Navisworks API subsystems were developed to enhance efficiency.

4.5. API Module for Explanation of Modifications. This module allows users to edit the brief summaries used for explaining modifications made to the BIM-FM models. Furthermore, the system automatically exports the brief summary to update the historical summaries of the modifications made for the selected modified BIM-FM model.

4.6. API Module for Information of the Modified BIM Model. This module allows users to store angle and distance information to explain BIM model modifications clearly and easily. This function can effectively illustrate the modified BIM model.

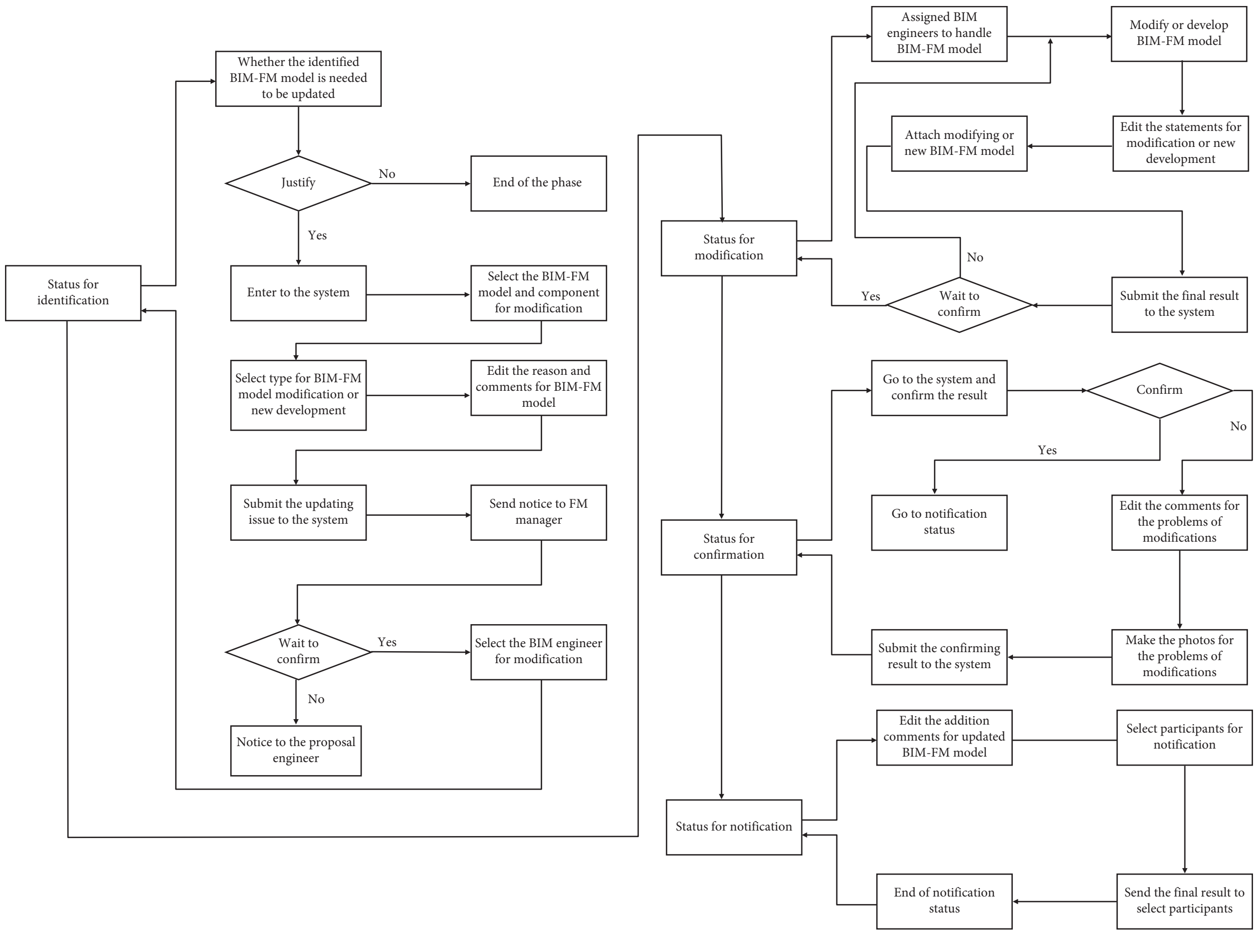

Figure 4: Main flowchart for management of BIM-FM models.

4.7. API Module for 2D Location with Errors. This module lets users edit 2D locations for required modification of errors or problematic locations. To enhance the effective modification of BIM models, this module allows users to mark the 2D map to show the modified location in the BIM model.

4.8. API Module for Automatic Model Transfer. This module helps users transfer and update new or modified BIM-FM models to the FM system without manual operation. In addition, the module will record and summarize details for the BIM-FM models transfer to the FM system.

5. Pilot Case Study

5.1. Case Study Implementation. To determine the advantages and limitations of the proposed approach and BFMM system, they were applied to a new office building in Taipei, Taiwan. This building mainly provides office space (a total floor area of approximately 18054 m^2) and includes 14 floors above ground and a four-story underground parking garage. BIM was implemented during the design and construction stages as the owner planned originally to use BIM to assist in FM implementation. Before the project was completed, the general contractor delivered completed as-built BIM models for the owner according to the contract. During the construction phase, all the as-built BIM models were developed and updated by general contractors and subcontractors based on all requirements of contacts. Finally, the general contractors updated and combined all the as-built BIM models for completed as-built BIM models at the closeout of the project. The completed as-built BIM models include completed as-built BIM models for architecture, structure, and mechanical, electrical, and plumbing (MEP). Furthermore, the general contractors were required to enter the nongeometric information of important completed as-built BIM models for equipment and facilities (such as information for equipment supply name and purchase time).

After the completed as-built BIM models were developed by the general contractor, they were handed over to the owner, inspected, and confirmed. The completed as-built BIM models received by the owner were continued to be updated with BIM-FM models added as necessary for FM, with the owner assigning one full-time BIM engineer and one junior FM engineer as a BIM part-time engineer responsible for the maintenance of BIM-FM models. The duration of the pilot study was fifteen months and the major participants included BIM engineers, FM engineers, FM manager, and suppliers (general contractors and equipment suppliers).

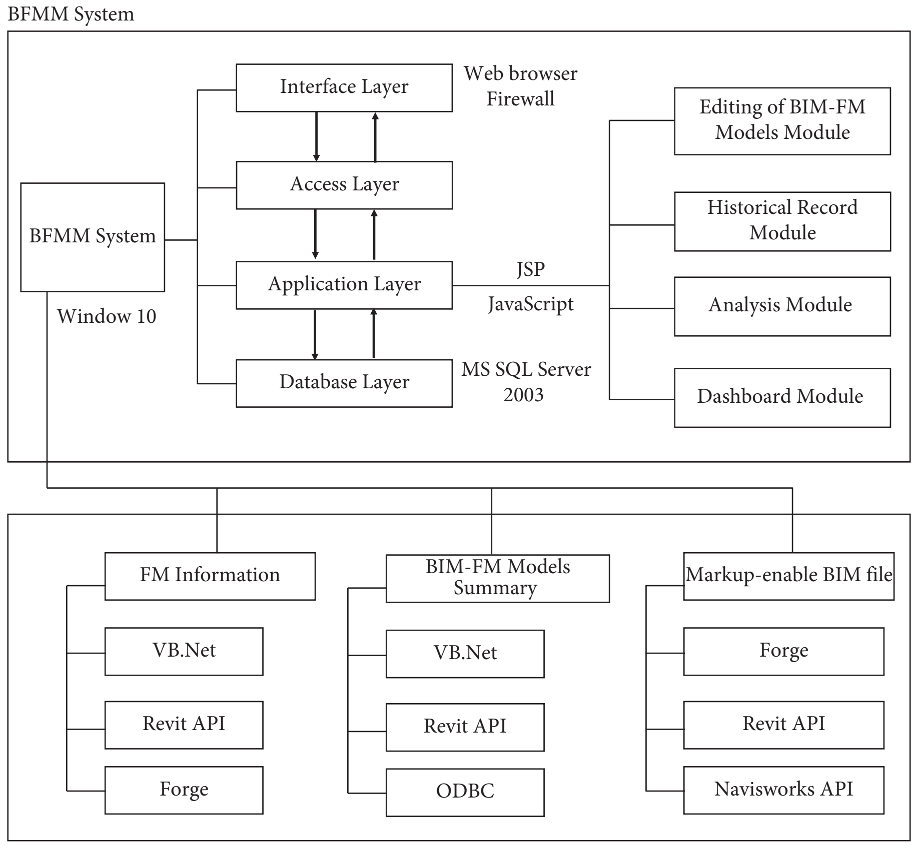

Figure 5: System framework of the MFMM system.

At the closeout of the building construction project, engineers under the general contractor were asked to prepare and submit the completed as-built BIM to the BFMM system. During the closeout stage, the engineers inspected the completed as-built BIM based on the contract requirements. Identified problems and suggestions to correct the BIM were communicated and responded to through the BFMM system, with related records and submitted documents collected and stored in the system. The general contractor then corrected and modified the model according to the comments. Once all issues were rectified, the completed as-built BIM was stored as the FM-based BIM. In the case study, the first edition of BIM-FM models was developed and submitted by general contractors at the completion of the case study. In the beginning of the operation phase, the BIM-FM models were updated as the second edition for the usage of interior decoration. After 10 months, a new department was added and moved in the building, and the interior design was modified again based on the new requirement. Therefore, the second edition of BIM-FM models was modified and updated into the third edition of the BIM-FM models. Furthermore, another new office was added for the interior design, which was required to be modified for the fourth edition of the BIM-FM models. The fifth edition of the BIM-FM models was updated with the new facilities that were purchased and added in the office. Finally, the fifth edition of the BIM-FM models was also updated into the BFMM system for BIM-FM models management in the case study. Figure 6 shows the management of BIM-FM models in the case study. Figure 7 shows the use of the BFMM system for management of BIM-FM models in the case study.

5.2. Discussion. After the pilot case study, the system was verified to evaluate the system usage. All related participants were required to answer the questionnaire and provide feedback. The participants included two FM managers, ten FM engineers, two BIM engineers, two engineers of general contractor, and three suppliers. Table 2 illustrates the results of the system usage evaluation. Table 3 summarizes the comments from the system evaluation.

The following are the key questionnaire results that highlight the major benefits of the BFMM system. First, 92% of the respondents stated that the system effectively records all historical information on the FM-based BIM. Second, 89% agreed that it displayed all recent results and statuses for newly developed or modified FM-based BIM models during the project. Finally, 90% agreed that the system confirms the correctness of the new or modified FM-based BIM models.

Figure 8 demonstrates the percentage for the major problems of BIM-FM models based on the case study. There are 176 total different problems encountered in the case study. As shown in the figure, most respondents reported existing problems related to no updated BIM-FM models (28%), no BIM-FM model developments for new facilities (28%), and having insufficient time for new developments or

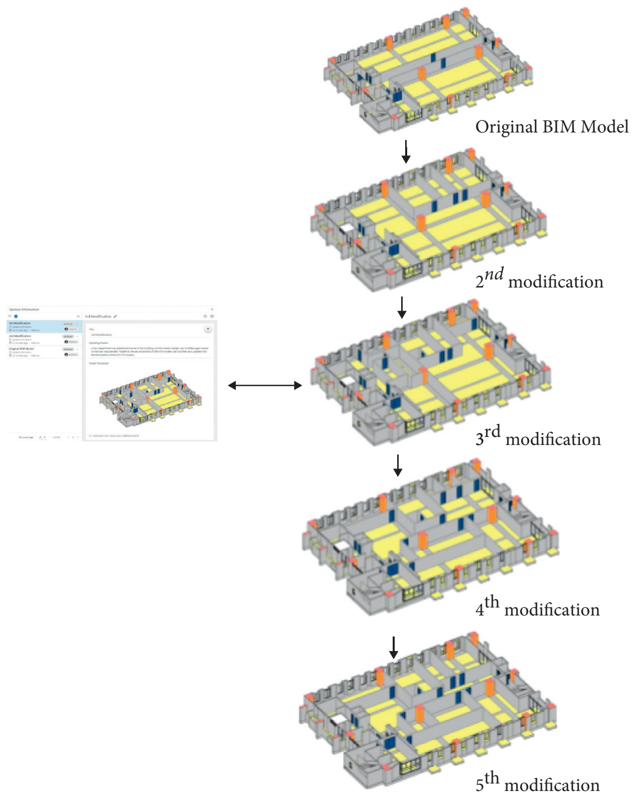

Figure 6: The management of BIM-FM models in the case study.

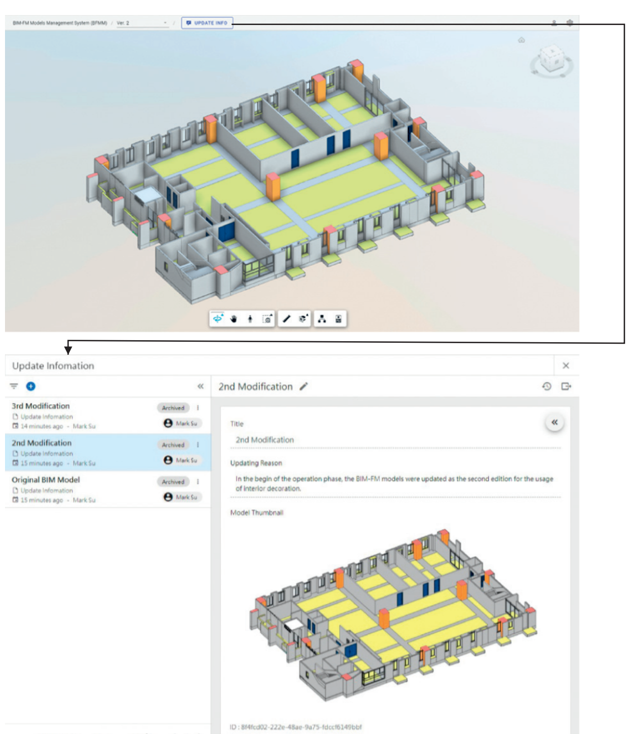

Figure 7: The use of the BFMM system for modification record of BIM-FM models in the case study.

updating (20%). Fewer respondents reported problems related to incorrect BIM-FM model developments (14%) and lack of expertise for BIM-FM works (10%).

Figure 9 displays the difficulties in the implementation of the BIM-FM model management in the case study. There are 123 total different difficulties encountered in the case study. As shown in the figure, the majority of respondents reported difficulty in providing sufficient incentive for implementation (22%), having insufficient manpower for implementation (20%), having inadequate responses for clients (18%), having insufficient time to develop new models for new facilities (16%), and having insufficient time to update and modify the models (15%). By contrast, few respondents reported difficulties in problems for lack of BIM-related expertise for implementation (9%).

We identified the following limitations and barriers for the proposed BFMM system:

(1) No BIM engineer was hired in this project. Therefore, the management of the BIM-FM models was done by one of the full-time FM engineers. Although this FM engineer has the BIM skills to handle the modification of the BIM model, they lacked the time to perform these modifications. Without full-time BIM engineers to handle BIM-FM models, a situation can arise where there are no persons to perform the maintenance management of the BIM-FM models. Most FM engineers are occupied with their primary responsibilities and are not available for part-time tasks for the modification of BIM-FM models.

(2) Based on the case study results, another problem is the entry of nongeometric information in the BIM model. There are serious problems regarding missing nongeometric information in the BIM models, which, in the case study, include information about the model of the equipment, information about the purchase time of the equipment, information about the maintenance of the facility, and basis required information about regular maintenance of important equipment or facilities (such as elevators). The missing nongeometric information in the case study can be explained by three important reasons. First, most of the paper-based handover documents for equipment and facilities submitted by suppliers do not include the required nongeometric information. Second, it is ineffective for general contractors to enter the nongeometric information for completed as-built BIM models from paper-based handover documents at the closeout of the project. Third, engineers for the general contractors and equipment suppliers may not have sufficient time to enter the nongeometric information of a BIM model, depending on the contract requirements.

(3) In the case study for FM engineers and FM managers or owners, it is still challenging to inspect the completed as-built BIM model provided by the general contractor. The requirements for the

Table 2: The result of system usage evaluation.

Title description	Mean score
Applies suitable BIM use for FM	4.24
Ease of use	4.12
Clear user interface	4.32
Reduces rework time	4.18
Effectively tracks modification results of BIM-FM models	4.52
Effectively accesses historical record of modifying BIM-FM models	4.43
Enhances correction management of BIM-FM models modification	4.72
Improves workflow management of BIM-FM models modification	4.38
Improves data reentry problems for BIM-FM models	4.16

Note. The score for mean is calculated based on respondents' feedback using a questionnaire with a scale of 1–5 (1 indicates strongly disagree and 5 indicates strongly agree).

Table 3: System evaluation comments.

No.	Participant comments
1	FM engineer: It is very convenient for me to access the latest BIM model for FM. I used to utilize the cloud-based database to store the BIM model. However, the solution is not efficient for me for maintenance management of facility BIM models for FM use.
2	FM engineer: It is effective for storing all updated BIM models for FM use when a BIM model is updated or a new BIM model is developed for a new facility using the proposed system. The proposed system provides an effective platform for sharing the latest FM BIM model for FM use.
3	FM manager: It is very important for me to inspect all available BIM models for FM for the building. I may refer to all previous updated BIM models to compare the differences through the system. All ongoing or delayed work for maintenance management of facility BIM models can be managed and tracked effectively by the system.
4	Owner: Regarding the application of BIM for FM, it is very important to keep the BIM model for the latest status. Therefore, it is necessary to provide a platform for the management of BIM models of facilities. Although there are many commercial software programs designed and developed for various BIM applications, there are few systems developed specially for the management of maintenance of BIM models of facilities.
5	BIM engineer: I think that the system is necessary for the application of BIM for FM. Especially for changes to the space or decorations of a building, the modification of BIM models can be executed and confirmed before the use of FM. The system can help us to collect, trace, and manage all submissions of updated BIM models. The system is different from other current software.
6	Equipment supplier: It is a great idea for us to submit the BIM model for newly purchased equipment through the system directly. After submitting the BIM model of the new equipment, the system will illustrate the summary information and automatically check if the required information of BIM model meets the requirements.
7	FM manager: By using the proposed BFMM system, it is very convenient for me to access and understand the current state for BIM-FM models management. Without the use of BFMM, it is difficult for managers to handle and manage all BIM-FM models for different buildings.

completed as-built BIM model will vary depending on the contract, and the contents and results are manually inspected and confirmed. Therefore, a large amount of time and effort is still needed to check the BIM-FM models.

(4) It is strongly suggested that the BIM-FM models for an equipment should be developed by the equipment suppliers. Facility suppliers will easily and effectively understand the relevant important information for the BIM-FM models of the equipment. Furthermore, they will understand variances between the different types of equipment. Therefore, it is suggested that equipment suppliers should provide the BIM models for facilities with related important information when they sell facilities.

(5) In this case study, the owner assigned the owner-operator the responsibility of handling the BIM for FM. The proposed management mechanism and flowcharts will differ if owners handle the management of BIM-FM models through FM service providers (BIM outsourcing services).

(6) In the maintenance and management stage, the maintenance personnel of the maintenance management BIM model and the maintenance management-related personnel are not necessarily the same group. When the maintenance management-related personnel complete the maintenance work, how to notify the maintenance management BIM model maintenance personnel about the communication mechanism of the update content is an important issue. Past experience in Taiwan Maintenance BIM shows that maintainers and maintenance management-related personnel do not have a communication channel, resulting in problems for maintenance BIM model maintainers, such as not knowing when to update and what contents to update.

(7)In the operation stage, most FM departments will not hire a full-time BIM engineer. The major reason is that the operation stage will require considerable BIM verification and correction operations at the beginning, and the usual workload is not very high after entering normal operation. Therefore, it is recommended that the FM department can train a

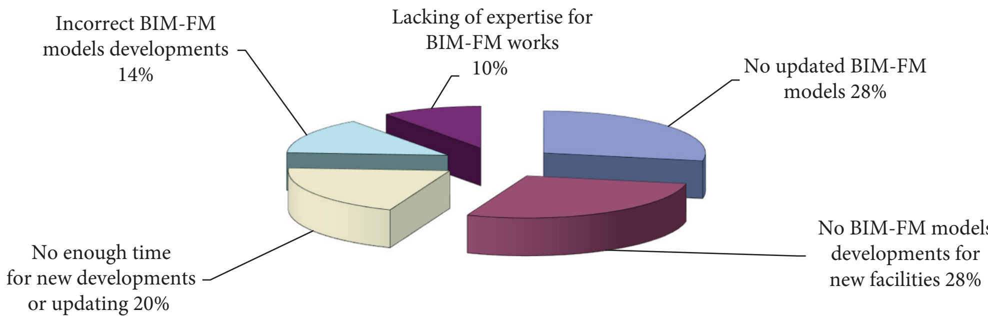

Figure 8: The percentage for the major problems of BIM-FM models works based on the case study.

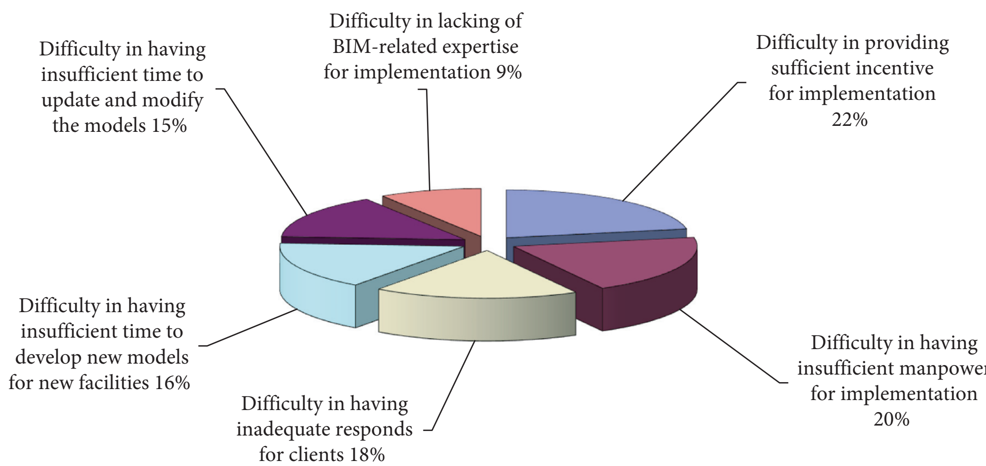

Figure 9: The major difficulties in implementation for BIM-FM models management in the case study.

part-time FM engineer or outsource the BIM-FM model for import. If the part-time FM engineer of the internal FM department is used, it is necessary to consider that the FM engineer cannot change the work content frequently. Otherwise, there will be no time for the FM engineer to handle BIM development and corrections if the FM engineer is too busy.

We summarize the following major suggestions based on the case study:

(1)For new equipment, the owner needs to develop a new BIM model if the equipment supplier does not provide a BIM model. It will take significant time and effort for FM engineers to develop a BIM model for the new equipment by themselves.

(2)It is necessary to set up the management mechanisms for BIM-FM models in advance. The management mechanism for BIM-FM models includes the initial plan, personnel involved, and control flowcharts for management of BIM-FM models. These management mechanisms will be identified and planned based on the requirements and organization for FM.

(3)When the maintenance work is outsourced, it is necessary to notify the maintenance and management BIM model maintainers of the updated content after the maintenance work is completed by the outsourced maintenance management personnel. In the past, it was difficult for the maintenance and management BIM model maintainers experienced in Taiwan to request the commission. External maintenance and management personnel provide sufficient information; hence, maintenance BIM model maintainers will face problems such as not knowing when to update and what to update.

(4)It is important to identify the requirements for BIM-FM models in advance. There are no BIM-FM models for select facilities, as the owner does not plan to use BIM for FM for these facilities (such as lights in the case study). Therefore, new BIM-FM models for these facilities were not required when the facilities were purchased during the operation stage. The owner needs to identify which BIM-FM models need to be developed for use in FM in advance; otherwise, time and labor will be required to develop unnecessary BIM-FM models.

6. Conclusions

In recent years, BIM has been regarded as one of the main visual tools for FM applications. When BIM technology is integrated with FM solutions, it is necessary and important to consider the effective management of BIM-FM models for the successful implementation of the integration of BIM and FM. Successful BIM-FM implementation is challenging without the effective management of BIM-FM models. Many previous research efforts and case studies have focused on FM-related applications and system development in academic and industrial fields. However, few studies have focused on BIM-FM management during the operation stage of a project. Furthermore, there are many commercial software programs developed for BIM application for FM, and the main purpose of these programs is to provide FM-related applications instead of BIM-FM management. This is the main contribution of this study, as compared to previous research and studies.

The objectives of this study were to (1) propose a management approach for BIM-FM models of building projects, (2) develop a management system for BIM-FM models based on the proposed approach, (3) apply this system to a case study in Taiwan to confirm the effectiveness of the proposed approach and system usage specifically for the management of BIM-FM models, and (4) identify the major advantages and limitations of the proposed approach and system.

The major suggestions derived from this study are as follows: (1) BIM-FM models should be updated frequently to confirm the accuracy of the BIM-FM models; (2) the FM department should carefully plan and set up the management mechanisms for BIM-FM models based on requirements; (3) top management should support the management of BIM-FM models if the owner plans to utilize BIM technology for FM; (4) owners should rely on their owner-operator FM organization to handle BIM application for FM; and (5) facility suppliers should provide the BIM models for facilities with the relevant important information when they sell facilities.

Owing to the different types and attributes of FM organizations, the roles and management processes mentioned in this study will vary; nevertheless, the proposed core concepts and methods in this study remain relevant. These roles and processes can be adjusted and modified based on FM organization types and attributes to meet the requirements and purposes of management of BIM models for FM in the FM organization.

Further steps are required to continue to develop and link the BFMM system and the BIM-based FM systems. With assistance provided by the BFMM system for the owner, updated BIM models can be collected and managed effectively during the operation stage. Furthermore, the updated BIM models delivered by the BFMM system can enhance the successful implementation of BIM-based FM systems.

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

The authors would like to acknowledge the National Science Council, Taiwan, for financially supporting this work (Grant no. 110-2622-E-027-033-) and express their appreciation for all involved project participants' assistance.

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Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 8556714, 22 pages
https://doi.org/10.1155/2022/8556714

Research Article

A Framework of Selecting Building Flooring Finishing Materials by Using Building Information Modeling (BIM)

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Received 13 September 2021; Revised 11 December 2021; Accepted 7 February 2022; Published 25 February 2022

Academic Editor: Alberto Sanchez

Building materials selection is a critical process affected by many complicated factors. Due to the specific function of elements, alternatives to materials must be appropriately chosen as they differ in quality, performance, and cost. Implementing a Value Engineering (VE) process is challenging as it requires effort and several workshops. Thus, this study proposes a framework to automate the VE process of selecting building flooring material. The framework identified selected agreed criteria of flooring finishing materials measured based on agreed standard tests. The developed framework is distinguished from other current research using a combination of Analytic Hierarchy Process (AHP), Pairwise, and Function Analysis System Technique (FAST) methods to define the criteria ranking weight and include the building function. Furthermore, the framework is integrated with Building Information Modeling (BIM) that has been widely used in the Architecture, Engineering, and Construction industry (AEC). Finally, a case study of a residential house in Saudi Arabia was used to demonstrate the framework. The proposed framework was verified by using two questioners and expert consultations.

1. Introduction

The construction industry is one of the crucial sectors in the world. It enhances economic growth due to its effect on other economic areas [1]. The appropriate building materials selection and recommended construction details seriously affect the project's cost [2]. Moreover, their consumption value is about 40% of any project's total cost [3]. The designer ensures that the choice of materials is perfect in his/her proposed design. Value Engineering (VE) is a method for improving building material selection. Many researchers, in recent times, studied the application of VE in the selection process within construction [4–10], and [11]. Wao [12], Latief et al. [13], Wao [14], Yu et al. [15], and Li et al. [16] focused on using the VE to improve the building's sustainability rate. Ekanayake and Sandanayake [17], and Mao et al. [18] made an effort to simplify the process of VE by integrating VE via lean management. Wei and Chen [19] utilized BIM energy-saving simulation to develop a judgment model through VE for optimizing green building design. Usman et al. [20] also utilized BIM associated with VE. Through review study of these researches, it can be noted that there is a need to make the process of VE more programmed and regular, which can be done by designing a model to simplify this process. Three significant factors of VE require to be addressed: quality, function, and cost. To achieve the optimal and higher value choice, the owner wishes to obtain the maximum quality performed function, achieving the minimum cost. Dell'Isola [21] defined the relation of these three factors in the following formula:

$$\text{Value} = \frac{\text{Function} + \text{Quality}}{\text{Cost}}. \quad (1)$$

Regarding cost, the criterion is quite clear since it has a measurable unit to compare numbers, while the quality evaluation is complex to measure since quality is affected by several criteria measurement units. Therefore, these criteria should be identified, weighted, and linked with material function. Othman [22], Fan and Shen [23], Marzouk [24], Wei and Chen [19] utilized function analysis in their studies.

Many materials are available in the market with different specifications. These materials' variety makes the selection task relatively complicated. Besides that, the current construction trends require an implication of a more widespread scope of evaluation criteria, which increases the complexity of the material selection process [25].

Floor finishing materials are one of the critical items in any construction project. They are defined as the material used to cover the floor, as these materials provide the required quality and at a moderate cost [26]. AL-Oqla and Sapuan [27] stated that the material selection process is one of the tasks that engineering design requires. Based on the VE concept, a wide variety of flooring finishing materials is chosen. This selection method will help the decision-makers to select the most valuable materials.

There is a demand for a systematic approach to automate these selection methods due to comparing a wide different variety of flooring finishing materials. Many international standards measure the building material quality using a standard test and assign a minimum value of accepted quality measurement unit. Some countries have their material standards, such as Saudi Standards, Metrology, and Quality Organization (SASO) [28], adopted from the international standard. These material standards can be used as a base to create and measure criteria for building material to be more objective and be able to be automated. The cost and quantities of the material building are other factors that need to be controlled to simplify the VE concept selection process.

The fifth dimension of Building Information Modeling (BIM) deals with material cost and quantity [29]. Hence, BIM can be adapted to facilitate and automate the process. BIM is described correctly as a model designed on a technological basis, connected with a project information database that is readily accessible and retrievable for detailed estimation of construction, proposed project schedules, and project management. This helpful design technique can assure higher productivity, enhance quality, and secure the project delivery schedule at a minimum cost [30]. Furthermore, BIM tools provide an efficient platform for implementing other constructive model features [31]. For example, Li et al. [32] demonstrated the significance of integrating BIM and VE using the proposed framework and applying it to Chines high-rise buildings to control construction cost and optimization.

The VE right now depends mainly on shared experts' information and data, making it a more abstract method. This impediment makes VE implementation more avoidable, as mentioned in previous papers [9]. A solution to respond to this challenge is to automate the VE process. This study introduced a framework model to attempt automated the material selection process for building floor finishing materials utilizing the concept of VE. The study also defines the selection criteria based on international standards, research, and expert knowledge. Measuring selection criteria (including material quality) varies from one country to another. However, it can be customized to a specific country, such as Saudi Arabia. These criteria can be measured based on a standard test or agreed on weight to be programmed and easy to use by the practitioners.

Moreover, the novelty in the developed framework is identified general eleven selection criteria of finishing selection material. These selection criteria were measured and ranked based on standard test and weighting values using a methodology that integrates the Analytic Hierarchy Process (AHP), Pairwise, and Function Analysis System Technique (FAST) methods that are not done before. In addition, the framework is integrated and automated within BIM. The BIM framework model allows users to use the relative weight of ranking the selection criteria according to the building's material function. If building material is automated in such a manner, VE can be utilized efficiently during the design process as a guideline to achieve the optimal VE for the entire building design and encourage the practitioners to implement VE.

2. Literature Review

This section presents a range of literature reviews dealing with the methods and stages of the material evaluation and former studies related to Multi-Criteria Decision-Making (MCDM) and flooring materials.

2.1. Material Evaluation Process and Methods. Due to the vast number of available materials, managing and verifying the material selection process is a challenging task. The current construction trends require a broader scope of evaluation criteria [26]. The material selection has been broadly covered in writing through numerous methodologies [33]. MCDM has been used as a research tool since the year 2000 up now [34]. MCDM simplifies complex problems to the natural form to become a prevalent method for solving decision-making problems in many areas. One of the MCDM applications is a material selection [35]. Table 1 summarizes some of the papers.

2.2. Value Engineering (VE). VE is organized to provide the required facility with the lowest total costs, consistent performance, reliability, and maintainability [24]. The current construction practices require an inordinate effort to balance money, time, and quality. The Society of American Value Engineers defines VE as the systematic application that identifies and provides the necessary function reliably at the lowest overall cost. VE improves service value by modifying and enhancing functions. The fundamental objective of VE is value improvement. Value, as defined, is the ratio of integrating function and quality to the cost [45].

2.3. Analytical Hierarchy Process (AHP). Saaty [46] had put forward the AHP to address the hierarchical problems by downsizing complex decisions. Hence, the AHP contributes to pinpointing a decision's subjective and objective dimensions. Furthermore, the AHP involves an efficacious technique and reduces any possible bias in the decision-making process. The AHP has become a flexible and efficient tool to obtain final ranking by evaluating the criteria and user options relatively using the pairwise method [47].

Table 1: Summary of formal papers in selection process.

References	Purpose	Techniques
Yazdani [36]	Material selection	AHP, FARE* and WASPAS*
Shahinur et al. [37]	Material selection	DSS and fuzzy analysis
Jadid [38]	Material selection	DSS
Venkata and Davim [39]	Material selection	AHP and TOPSIS*
Sefair et. al. [26]	Material selection	OSM
Usman et al. [20]	Material selection	AHP and BIM
Alhammad and Zanklo [40]	Material selection	AHP, VE, and BIM
Alrahhal Alorabi et al. [41]	Material selection	AHP, VE, and BIM
Yang [42]	Material selection	AHP and DSS
Abdallah, et al. [43]	Green building measures selection	DSS
Jalaei et al. [44]	Building components selection	DSS and BIM

*Refer to Abbreviation table.

2.4. Material Evaluation Criteria. Several solutions are usually considered to select the best building design alternative. These solutions should be optimally evaluated [48]. Some researchers restrict themselves to evaluating the material alternatives according to the cost and environmental criteria [26, 49], and [50]. Other studies evaluated energy criteria versus cost criteria in comparing alternatives [51]. On the contrary, some researchers evaluate material alternatives, including quality, performance, durability, and cost [48, 52].

2.4.1. Water Absorption. Water absorption is defined as "percentage of water impregnating the body of a tile, measured under ISO 10545-3" determination of water absorption, apparent porosity, apparent relative density, and bulk density. The fundamental property of floor finishing materials determines water's effect on the flooring surface. Water absorption can be classified based on low, medium, and high. Low water absorption enhances durability, especially when tiles may be subjected to heavy loads and high foot traffic levels [53].

2.4.2. Breaking Strength. It is an important criterion that affects the durability of the flooring. The higher breaking strength shows the higher quality of the tiles [54]. According to ISO 10545/4, breaking load is necessary to break the specimen. Also, the ISO specs defined the breaking strength as the force obtained by multiplying the breaking load by the ratio (span between support rods)/(width of the test specimen) [55].

2.4.3. Modulus of Rupture. The mechanical property of floor finishing materials is the rupture modulus, defined as dividing the breaking strength by the square of the minimum thickness along the fractured edge. A higher tear coefficient indicates higher tile quality [55].

2.4.4. Abrasion Resistance. Tile surface resistance to abrasion is determined by rotating the abrasive load on the surface and visually evaluating the abrasion results (ASTM C1027-19, 2019). Abrasion is, therefore, a crucial aging factor for natural stones. The abrasion causes a decrease in the mechanical properties and variations in the aesthetical characteristics, such as color and brightness [56].

2.4.5. Surface Hardness. It indicates the ability of the tile surface to resist abrasion and scratches. It also represents surface durability and aesthetic properties. It is measured using the Mohs scale [57].

2.4.6. Coefficient of Friction. This standard affects building design, as industrial and recreational buildings. It is essential for easy cleaning, draining, and similar work [58].

2.4.7. Thermal Conductivity. Low-water absorption floors have high thermal conductivity. Therefore, low thermal conductivity floors are unsuitable for radiant floor heating applications. Al_2O_3 particles play an important role in increasing the thermal conductivity to 50% when adding 20% to the ceramic paste [59].

2.4.8. Stain Resistance. Many materials cause stains on the surface of the tiles. Therefore, stain resistance is considered the most sophisticated quality standard that must be achieved due to the possibility of interactions between these materials and the tiles' surface [60].

2.4.9. Frost Resistance. Frost Resistance is directly related to the tiles' water absorption property. Exposure of tiles to temperatures below 0°C causes the absorbed water to freeze, causing the tiles to expand and break. Thus, the tiles are frost-resistant or nonresistant [61].

2.4.10. Chemical Resistance. Chemical resistance refers to the ceramic surface's behavior when exposed to chemicals that corrode it to permanently penetrate it or alter its aesthetic appearance due to its composition and properties. The deterioration of the surface of ceramic tiles caused by chemicals generally includes two different effects of the mechanisms, chemical, and physical action. Chemical action is the ceramic surface change due to a reaction between the chemical and some surface components. Physical action is due to the adsorption of chemicals that penetrate the surface to settle permanently, making it difficult to remove [62].

2.4.11. Thermal Shock Resistance. Thermal shock refers to sudden and unexpected changes in the temperature of floor or wall tiles due to contact with hot or cold objects (such as boiling water or cleaning steam). Due to thermal shock resistance, a tile can withstand such events without damage [63].

2.4.12. Crazing Resistance. Crazing is a typical and occasional effect consisting of subtle, irregular-shaped cracks in a tile's glaze. Generally, in a Ceramic tile, crazing is considered a defect. However, in particular cases, it can be a deliberate effect, intentionally created during production to give the surface an "antiqued" look. The causes of crazing are due to an incorrect dilatometric ratio between glaze and support. Construction or environmental conditions cause fine cracks in the glaze, termed as crazing [64].

2.4.13. Maintainability. Maintainability measures the easiness of retaining or restoring an item to a particular condition within a given time during the maintenance performance [65]. Usually, the maintainability factor dramatically affects the selection of material that needs heavy maintenance. This criterion has a direct impact on calculating material LCC.

2.4.14. Durability. Durability refers to a product's ability to fulfill its essential function for an extended period under normal usage conditions without requiring significant maintenance or repair [66]. The durability factor becomes critical building materials selection criteria for heavy usage such as Heating, Ventilation, and Air Conditioning (HVAC), flooring, and similar material types.

2.4.15. Buildability. The amount to which a structure's design allows ease of construction, subject to the overall necessities for completing a building, is known as buildability [67]. Usually, this factor requires the contractor's experience with construction methods for installing building materials. Ferguson [68] defines buildability as "the ability to construct a building efficiently, economically and to agreed quality levels from its constituent materials, components, and subassemblies." Buildability factors can include labor skill, supervision, complexity, working duration, types of material used, site layout, availability of power tools, the proportion of work done by a subcontractor, etc. [69].

2.4.16. Aesthetic. Aestheticism is an essential criterion for floor finishing materials. The visual impression of the flooring types, color, and surface finishing quality forms the aesthetic characteristics of the floor of finishing material [70]. In contrast, this criterion may significantly increase the cost of these materials.

2.4.17. Sustainability. Sustainability is the fulfillment of the requirements of people and society by employing technology and practice optimally throughout the building's life cycle [71]. These parameters and their weights differ from one system to another due to environmental, regional, and cultural conditions [72].

3. Research Methodology

This section defines the research methodology that followed to achieve the study objective, which develop a framework of selecting finishing materials of building flooring utilized VE concept. Figure 1 shows the flowchart of the research process phases. The study's first phase collects many formal studies and standards to understand the framework's requirements. The next phase is to develop the framework using four research methods: VE, AHP, FAST, and Pairwise. The following section is a full explanation of developing this framework. The following phase task is to program the framework within the BIM platform. Then, applying the developed automated framework to a case study for validation. The final phase is to discuss the case study result and validate the framework by consulting three experts and questioners, which will be explained later.

3.1. Phase 1: Collecting Data. This phase has a comprehensive search on published papers, reports, catalogs, and standard manuals. In addition, several meetings with material suppliers during the exhibition events or visiting the flooring stores. This task aims to understand the needs and missing gaps in selecting the floor materials. The outcome of this task is to develop a plan and methodology for implementing the introduced framework.

3.2. Phase 2: Develop the Framework of Selecting Finishing Materials of Building Flooring. This study's framework depends on predominant criteria based on previous literature reviews, international quality standards, and expert questionnaires. Several international quality standards are used to determine the material's required quality (ISO, SASO, ASTM, and EN). SASO [29] adopted many of these standards in Saudi Arabia. This research studied a long list of SASO criteria with different floor materials (Ceramic, Marble, and Porcelain) to identify the most common criteria from this long list. Experts and quality engineers have been consulted to perform this task.

The framework is designed to achieve the research objective. Figure 2 shows the framework of the material selection process that consists of six steps. These steps include five variables which are Criteria Weight (CW), Criteria Quality Weight (CQW), Quality Weight (QW), and Life Cycle Cost (LCC). These five parameters are used to calculate only one final variable, the Material Value Ratio (V). To simplify and better understand the relationship between these variables according to the AHP method arrangement, Table 2 shows the relations between all these variables in tabulated form for an example of three materials alternatives and three material criteria.

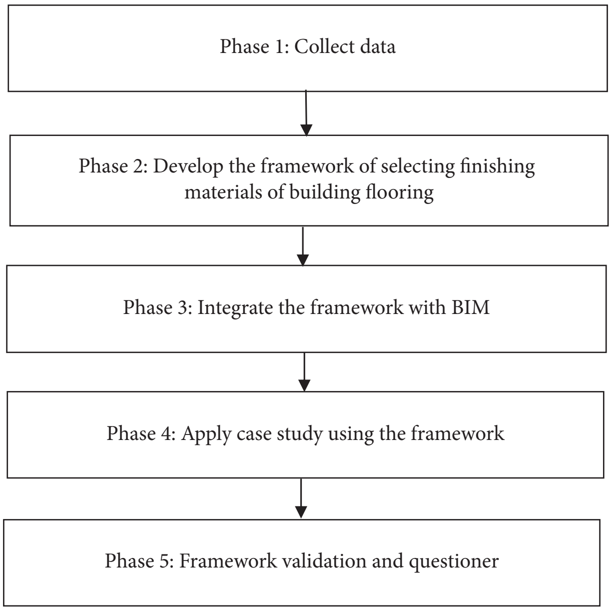

Figure 1: Flow chart of research methodology.

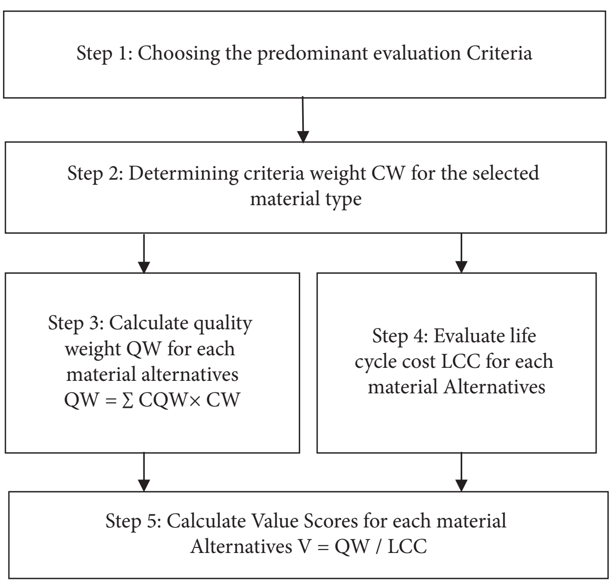

Figure 2: Framework of the material selection.

Table 2: The framework variables and calculation.

	Criteria weight	Material 1	Material 2	Material 3
Criterion 1	CW_1	CQW_{11}	CQW_{12}	CQW_{13}
Criterion 2	CW_2	CQW_{21}	CQW_{22}	CQW_{23}
Criterion 3	CW_3	CQW_{31}	CQW_{32}	CQW_{33}
QW		QW_1	QW_2	QW_3
LCC		LCC_1	LCC_2	LCC_3
V		V_1	V_2	V_3

The below steps sections represent the evaluating materials process applied to materials to be evaluated. It is then linked with the BIM Model to facilitate data input and automate the output accordingly. A case of a residential building was then studied and validated based on the proposed framework.

3.2.1. Step 1: Choosing the Predominant Criteria. This step establishes the essential evaluation criteria for the selected material by following several methods. One method is searching the literature review and grouping all these criteria into appropriate items. Another method is studying the international material standard. The goal of these standards is safety and health protection, measurement, analysis, quality control, and environmental protection [73].

The criteria upon which the evaluation is based include five main criteria categories: (1) material quality and standards, (2) aesthetic standards, (3) maintainability, (4) buildability, and (5) sustainability. The process of determining the predominant criteria was carried out in five tasks.

Task 1: Gather technical specifications for floors: By gathering and studying a range of flooring specs and standards, these standards have been classified and grouped based on the type of flooring. Table 3 shows the preliminary results obtained at this stage, showing the floor type with the standard and its reference in SASO [29].

Task 2: Reduce the repeated and unnecessary flooring criteria: The unrelated criteria required to be eliminated to simplify the evaluation process.

Task 3: Determined the used standards in this study: By visiting SASO [29] and discussing the quality standards affecting the types of floors with specialists in the field, a list of agreed standards has been developed to be used in the research.

Task 4: Define the final criteria to be used in this study: A list of twenty-one criteria was presented to experts in an official questionnaire to determine the most common and influential criteria in selecting floor finishing materials (refer to questionnaire and validation section). The results of previous steps showed that the following eleven criteria are the most common, as shown in Table 4.

Tasks 5: Determine the optimal reference values of each measurement criteria test: After setting the eleven criteria, there is a need to define the flooring material quality level for each of these criteria. For this purpose, the optimal reference values for each material criterion have been determined through experts' verbal and validated using a questionnaire (refer to questionnaire and validation section). Table 4 shows these optimal values, called in this paper "optimal CQW," as will be discussed later in Step 3.

3.2.2. Step 2: Determine the Framework CW. VE concept uses function analysis as a factor for selecting material. FAST is a popular method to assess material function [21]. This final output technique determines the logical relationships between functions of material. However, the method does not calculate the weight for each function item and does not include functional analysis in the procedure [75, 76].

Lin and Yang [77], Liu and Hai [78], and Hamdan and Cheaitou [79] use the hierarchy analysis chart in their analysis without functional analysis. This study differs from other methods in integrating FAST and AHP methods for

Table 3: Preliminary results obtained from suppliers and factories.

Flooring type	Test method	Standard
Ceramic	Definitions, classification, characteristics, and marking	SASO-ISO-13006
	Determination of frost resistance	SASO-ISO-10545-12
	Determination of moisture expansion	SASO-ISO-10545-10
	Sampling and basis for acceptance	SASO-ISO-10545-1
	Determination of linear thermal expansion	SASO-ISO-10545-8
	Determination of resistance to stains	SASO-ISO-10545-14
	Determination of chemical resistance	SASO-ISO-10545-13
	Determination of resistance to surface abrasion for glazed tiles	SASO-ISO-10545-7
	Determination of crazing resistance for glazed tiles	SASO-ISO-10545-11
	Determination of lead and cadmium gave off by glazed tiles	SASO-ISO-10545-15
	Determination of slight color differences	SASO-ISO-10545-16
	Determination of modulus of rupture and breaking strength	SASO-ISO-10545-4
	Determination of resistance to thermal shock	SASO-ISO-10545-9
	Determination of resistance to deep abrasion for unglazed tiles	SASO-ISO-10545-6
	Determination of impact resistance by measurement of coefficient of restitution	SASO-ISO-10545-5
	Determination of water absorption, apparent porosity, apparent relative density, and bulk density	SASO-ISO-10545-3
Natural Marble Tiles	Methods of test for the natural marble tiles	SASO-1026
	Standard Specification for Marble Dimension Stone	SASO-ASTM-C503
Interlocking concrete paving blocks	This standard is concerned with interlocking concrete paving blocks.	SASO-1246
	Methods of test for interlocking concrete paving blocks	SASO-1247
Cement tiles	Specification for Cement tiles	SASO-1029
	Methods of test for cement tiles	SASO-1028
Vinyl	Sound insulation	SASO-ISO-717-2
	Colourfastness	SASO-ISO-105-B02
	Effect of chair castors	SASO-ISO-4918
	Reaction to fire	SASO-ISO-9239-1
	Thermal conductivity	SASO-ISO-10456
Parquet	Acoustical-Impact noise reduction	SASO-ISO-717-2
	Bond strength/Cross-cutting test	SASO-ISO-2409
	Broadleaved wood raw parquet blocks—General characteristics	SASO-ISO-3397
	Reaction to fire	SASO-ISO-9239-1
Carpet	Light fastness	SASO-ISO-105-B02
	Burning behavior	SASO-ISO-6925

defining the CW for all material criteria selection. CW's purpose in the AHP method is to determine the priority relation between criteria (criteria priority) [80]. The FAST analysis defines the CW to meet the project goal in this study. Zardari et al. [76] emphasized that many researchers overlook the difficulties in estimating CW. In this framework, CW can be calculated by the following these five phases:

(1) Phase 1. Determination of Project Goal and Function Analysis. The chosen materials must accomplish the project's key objective. Goals are essential to know the "what" and the

Table 4: The Optimum CQW for the eleven predetermined flooring material criteria.

No.	Criteria		The optimum reference value	Unit	International standard
1	Material Quality and Standards	Modulus of Rupture	50	N/mm^2	ASTM C 629
2		Breaking Strength	8000	N	ISO 10545-4
3		Surface Hardness	8	Mohs	EN 101
4		Abrasion Resistance	75	mm^3	ISO 10545-6
5		Water Absorption	0.01	%	ASTM C 615
6		Coefficient of Friction	0.25	μ	ASTM C1028
7		Thermal Conductivity	0.08	W/m·k	[74]
8	Aesthetic		5	Subjective	NA
9	Durability		5	Subjective	NA
10	Maintainability		5	Subjective	NA
11	Buildability		5	Subjective	NA

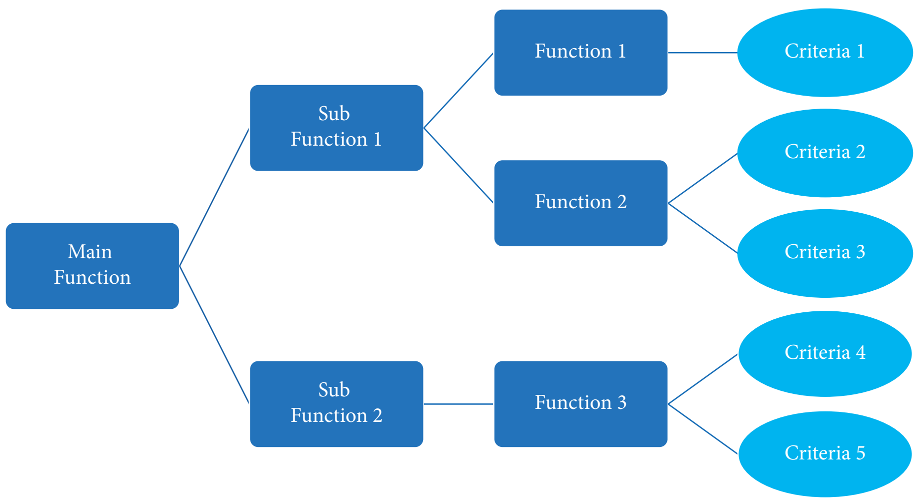

Figure 3: Main Components of FAST Diagram for a criteria weight's analysis.

"why" design. Also, function analysis plays a significant role in the VE process. If the function analysis is not appropriately determined, the material criteria would be weighted less accurately.

(2) Phase 2. Link the Criteria with Its Function/Subfunction/Criteria. This phase applies integration between the FAST and AHP/Pairwise method. Each criterion should be relevant to its function to accomplish this integration. Figure 3 shows an example of such integration. The rectangular shape in this figure represents the function analysis from the FAST method. On the other side of the figure, the oval shape represents the material criteria resultant from Step 1.

(3) Phase 3. Assigning Weights for All Function/Subfunction/Criteria on FAST Diagram. As shown in Figure 3, some functions may be linked to more than one criterion. Therefore, according to the following two methods, all criteria must be evaluated with assigned weights. According to Zardari et al. [76], the point allocation method is adopted when compared criteria in one level are less or equal to three. When greater than three, the pairwise comparison method is adopted. The latter method considers the expert judgment to evaluate the relative importance between each of the criteria against each other by using scale factors from 1 to 9. If the two criteria have equal importance, each has a value of one. Suppose one criterion is more important than the other; a scale of 2 to 9 is assigned as a factor of the importance degree. The method then developed a matrix and used equations to reach each criterion's weight described by Bhushan and Rai [75]. By the end of this phase, all functions/subfunctions/criteria are assigned a weight.

Figure 4 shows the integration of the FAST diagram with the assigned criteria, where each criterion is attached to its relevant function. After this integration, weights are given at each level of the diagram. As the selection of method is noted previously, therefore, the pairwise comparison has been employed when comparing the subfunctions (Resists Threats, Uses Safely, Attract Customers, Performs the desired function, Ease of Construction) as per the matrix shown in Table 5, and for functions comparison, as shown in Table 6.

(4) Phase 4. Calculation of DCW. After assigning all the criteria, functions/subfunctions on FAST Diagram, the next task is to determine the weight distribution between all linked criteria with function and subfunction. Each path may include function, subfunction, and criteria, as shown in Figure 4. The following equation shows the calculation of DCW [81]:

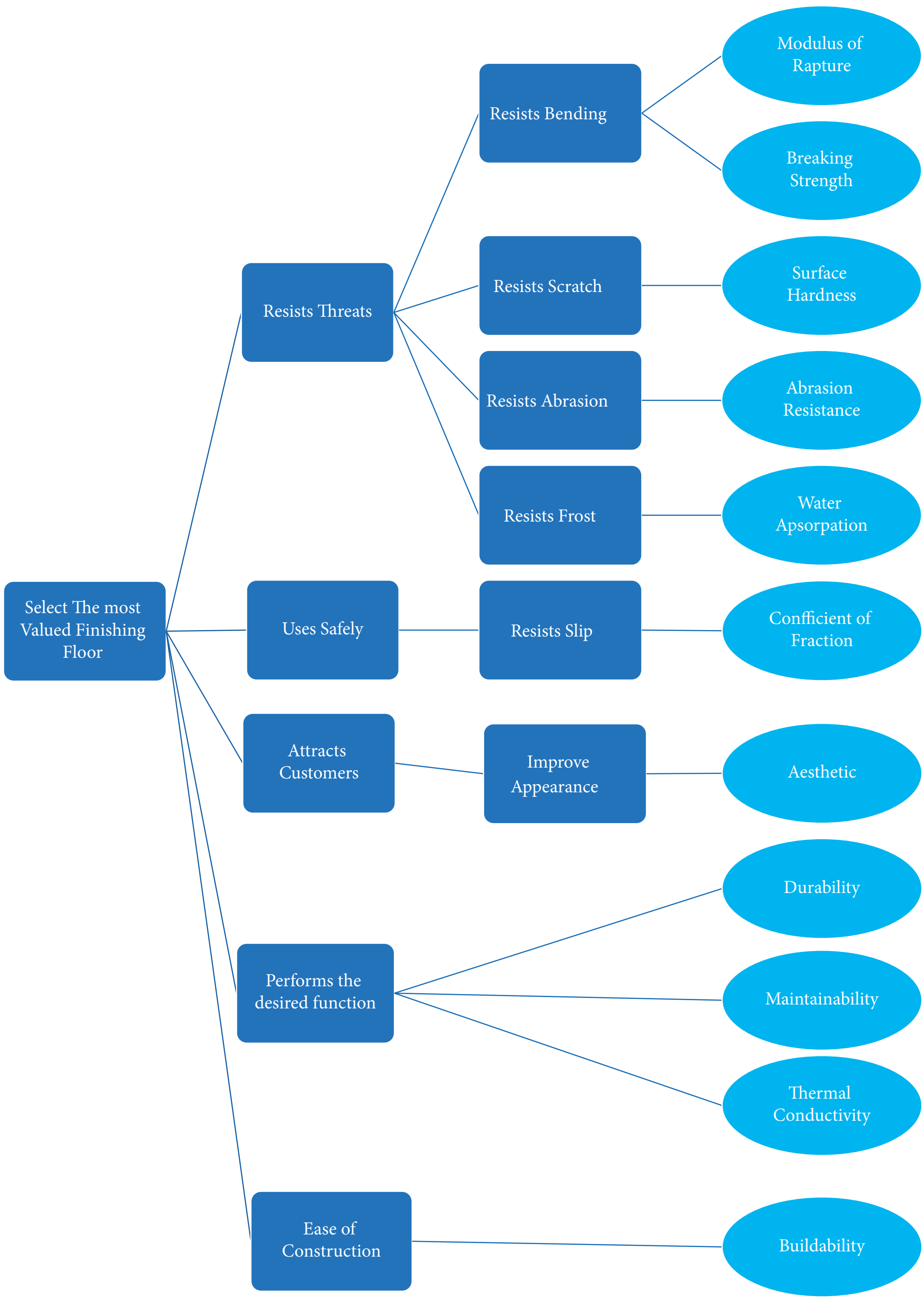

Figure 4: Criteria integration with FAST diagram of the project including CW.

$$\text{DCWeach path} = \text{Wfunction} \times \text{Wsubfuction} \times \text{WCriteria}. \quad (2)$$

Table 7 shows the 11 criteria linked with its function and subfunction. Also, the table represents the calculation of equation (2).

(5) Phase 5: CW Calculation. As a result of implementing the previous four phases, the DCW for all material criteria was assigned. Because of the possibility of linking material criteria to more than one function/subfunction, a need to sum all DCW that are related to one criterion, which represents the CW according to the following equation:

Table 5: The Pairwise comparison matrix (subfunctions).

	Resists bending	Resists scratch	Resists abrasion	Resists frost	W vector
Resists Bending	1	4	2	5	0.51
Resists Scratch	0.25	1	0.5	2	0.14
Resists Abrasion	0.5	2	1	3	0.26
Resists Frost	0.2	0.5	0.33	1	0.09
		$\sum W$			1

Table 6: The Pairwise comparison matrix (functions comparison).

	Resists threats	Uses safely	Attracts customers	Performs the desired function	Ease of construction	W vector
Resists Threats	1	2	0.5	0.33	0.5	0.13
Uses Safely	0.5	1	0.25	0.25	1	0.09
Attracts Customers	2	4	1	1	2	0.3
Performs the desired function	3	4	1	1	2	0.33
Ease of Construction	2	1	0.5	0.5	1	0.16
			$\sum W$			1

Table 7: Calculation of the DCW and CW.

1-function	2-subfunction	3-criteria	W_1	W_2	W_3	$\text{DCW} = W_1 * W_2 * W_3$	CW
Resists threats	Resists bending	Modulus of Rupture	0.13	0.51	0.4	0.03	0.03
Resists threats	Resists bending	Breaking Strength	0.13	0.51	0.6	0.04	0.04
Resists threats	Resists Scratch	Surface Hardness	0.13	0.14	1	0.02	0.02
Resists threats	Resists Abrasion	Abrasion Resistance	0.13	0.26	1	0.03	0.03
Resists threats	Resists Frost	Water Absorption	0.13	0.09	1	0.01	0.01
Uses safely	Resists Slip	Coefficient of Friction	0.09	1	1	0.09	0.09
Attracts customers	Improves Appearance	Aesthetic	0.3	1	1	0.3	0.3
Performs the desired function		Durability	0.33	1	0.3	0.1	0.1
Performs the desired function		Maintainability	0.33	1	0.4	0.13	0.13
Performs the desired function		Thermal Conductivity	0.33	1	0.3	0.1	0.1
Ease of Construction		Buildability	0.16	1	1	0.16	0.16
		$\sum$ CW					1

$$\text{CW for each Criterion} = \sum \text{DCW for all DCWs relate it to each criterion.} \tag{3}$$

However, none of the criteria are linked with more than one function/subfunction on this framework. Thus, DCW becomes equal to CW for all floor criteria, as shown in Table 7. For validation purposes, all the overall material CW should be equal to 1 (equivalent to 100%), represented at the bottom of Table 7.

3.2.3. Step 3: Calculating QW for Each Material Alternative. Now, the material QW calculation is done through three phases.

(1) Phase 1. Define the CQW for Each Criterion. As mentioned in the first step of framework methodology, each criterion quality needs to be measured according to international tests or other sources such as the manufacturer's information, manuals, material catalogs, information available from contractors, specialized consultants, and other literature [82].

The next task, these measured agreed tests, needs to be applied to different materials, ranging from low quality to high one, for defining the material quality classification. In case the criterion is not measured, the CQW needs to be weighted subjectively based on the experience of design professionals. 1-5 scale is used where the value ranges from 5 is excellent to 1 as inferior.

(2) Phase 2. Normalize the CQW Value for Each Material Alternative. To use the CQW in calculating QW, it first needs to normalize these test values to be scaled from 0 to 1. The summation of all CQW for each material alternative should be weighted to 1 (equivalent to 100%). Normalizing CQW makes it easy to read and measure. One method for normalizing a value is Linear Scale Transformation Max Method (LSTMM) [83]. In this study, the following equations can be used to normalize quality and LCC:

Table 8: Added parameters for the proposed framework.

Parameters group	Parameters names	Assigned category	Parameter name prefix	Parameter type
Criteria Parameters	CR.01.Modulus of Rupture CR.02.Breaking Strength CR.03.Surface Hardness CR.04.Abrasion Resistance CR.05.Water Absorption CR.06.Coefficient of Friction CR.07.Aesthetic CR.08.Durability CR.09.Maintainability CR.10.Thermal Conductivity CR.11.Buildability	Flooring	CR. XX.	Number
Benefit	BC.01.Beneficial BC.02.Beneficial BC.03.Beneficial BC.04.Beneficial BC.05.Beneficial BC.06.Beneficial BC.07.Beneficial BC.08.Beneficial BC.09.Beneficial BC.10.Beneficial BC.11.Beneficial	Project Information	BC. XX.	Yes/No
Weights Parameters	WP.01.Modulus of Rupture WP.02.Breaking Strength WP.03.Surface Hardness WP.04.Abrasion Resistance WP.05.Water Absorption WP.06.Coefficient of Friction WP.07.Aesthetic WP.08.Durability WP.09.Maintainability WP.10.Thermal Conductivity WP.11.Buildability	Project Information	WP. XX.	Number
Cost Parameters	LCC Cost	Flooring	N/A	Number
Value Output Parameters	Normalized Cost Normalized Quality Value	Flooring	N/A	Number

$$Rij = \frac{Xij}{Xi\max}, \tag{4}$$

$$Rij = \frac{Xi\min}{Xij}. \tag{5}$$

Equation (4) for beneficial values.

Equation (5) for nonbeneficial values.

Whereas: *Rij*: Normalized value of material *i* for criterion *j*. *Xij*: Criterion value of the evaluated material. *Xi*max: Maximum criterion value. *Xi*min: Minimum criterion value.

(3) Phase 3. Calculate the QW for Each Material Alternative. Before proceeding to the next step, each material's final quality value (i.e., QW) needs to be calculated from CQW determined previously. This new QW factor can be calculated by multiplying corresponding CW and CQW together for each of the material criteria, as shown in Table 2 and according to the following equation:

Quality Weight for each material:

$$\mathrm{Qw}j = \sum \mathrm{CQ}wij * Cwi, \tag{6}$$

$i = 1$ to Number of Criteria. $j = 1$ to Number of Material. The QW calculations will be demonstrated later by using a case study.

3.2.4. Step 4: Evaluate the LCC for Each Material Alternative. To use the selected material's value ratio, LCC has to be evaluated for each material alternative. LCC includes initial cost, operating and maintenance cost, and may consider the material's salvage value at the end of the building's estimated life cycle period. The LCC can be affected by many variable factors that are difficult to solve in the exact equation. By the end of this step, it requires normalizing the LCC for the next step and comparison purpose, as explained previously using equation (4).

3.2.5. Step 5: Calculate the V and Select the Best Options. This study has developed a transparent methodology for applying VE to select the most valuable flooring finishing

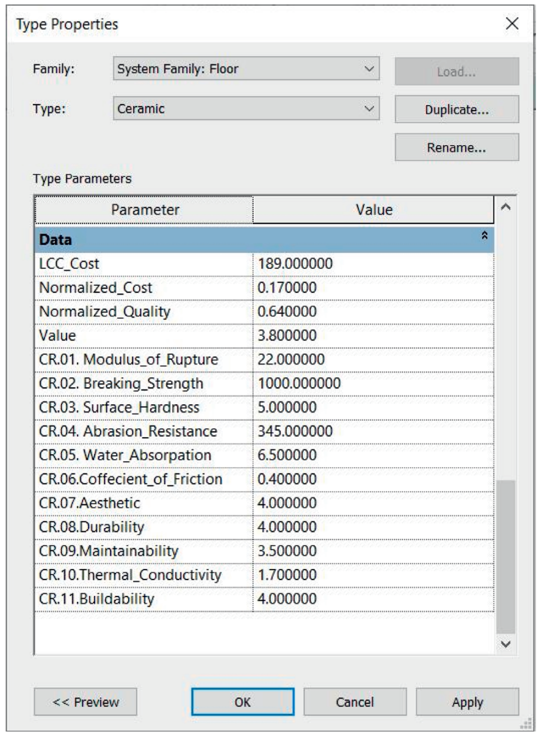

Figure 5: Window inputs for Criteria values of the case study BIM model, including the added parameters of the floor finishes.

materials. The most preferred material selection should represent the maximum quality score and the minimum LCC. The last two steps have the required two variables to determine the V as in the following equation, according to Dell'Isola [21]:

$$
\begin{aligned}
V &= \frac{\text{QW}}{\text{LCC}},\\
V &= \text{Material Value Ratio},\\
\text{QW} &= \text{Normalized material Quality Weight},\\
\text{LCC} &= \text{Normalized material Life Cycle Cost}.
\end{aligned}
\tag{7}
$$

By applying this equation for all material alternatives, each material alternative gets its value ratio (V). The VE concept's preferred material alternative is the highest V.

3.3. Phase 3: Integrated the Framework with the BIM. The primary objective of linking the proposed model with BIM is to help decision-makers select the optimal materials based on function, quality, and cost factors. For modeling the proposed approach using BIM, all data relating to the types of materials, their CW, QW, and V were included. The above evaluation process is linked to the BIM model through the "Application Programming Interface" (API). Furthermore, Dynamo programming is used in this research. It is an open-source visual programming tool that provides access to the Revit API in a more accessible manner. It gives users the ability to create programs visually by manipulating graphic elements called "nodes." Also, it gives the ability to access BIM data, write, edit, and automate repeated tasks. A *python* coding programming is a powerful tool that can extend the capabilities of Dynamo.

All criteria are defined as parameters in this framework to achieve the calculation process. The parameters in Revit can be assigned to any category. They allow the user to assign any data, and they can be linked with each other by a specified formula. Table 8 shows the parameters used in the calculation process. Some of these parameters are for data inputs, while others are for data outputs. Figure 5 shows the added parameters list. As noted, no spaces should be placed in the parameter's names because spaces may lead to programming errors. Also, a parameter name prefix code is defined to facilitate the programming. XX means that it is a place for two numerical characters. The following four steps are used in modeling the formwork.

(1) Modeling the floor finishing materials: All the materials alternatives were modeled. Materials specifications were specified.
(2) Entering the materials data: All quality criteria values are assigned. Besides, cost data were added. It could be entered manually or linked with an external database.
(3) Entering the project information criteria: All data relating to the project was defined, including the criteria' weights as per the project function analysis.
(4) Run the calculation program: After entering all inputs, the calculation process ran, selecting the materials with the best value was displayed. All alternatives were ranked, and output was displayed.

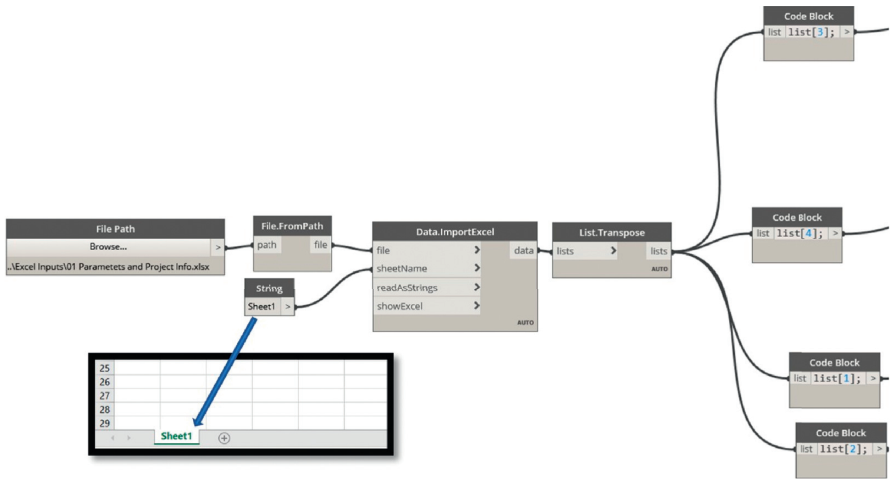

Figure 6: Importing spread sheet from Excel to BIM model by Dynamo.

Table 9: General information–residential villa–case study.

Building name:	Duplex villa
Building Type:	Residential
Project Area (m^2):	373 m^2
Country:	Saudi Arabia
City:	Riyadh
Address:	Malaga District
Project life span	30 years

Figure 7: Building Elevation of the case study.

Figure 6 displays the integration process between Excel sheet and BIM using Dynamo.

3.4. Phase 4: Apply Case Study Using the Introduced Framework. A case study of a residential building has been used in this research to understand the evaluation process better and validate it. The results and output are outlined to help the decision-maker select the material type that secures the best value. General information of the case study is shown in Table 9:

The building is a residential duplex villa. The building consists of a ground floor (Area = 208 m^2), first floor (Area = 213 m^2), and roof floor (Area = 210 m^2). Figure 7 shows a 3-dimensional model for the case study. The villa is under design, and the engineering office needs to coordinate with the owner to select the more valuable materials. One of the important decisions is selecting the flooring type available on the Saudi market. As a result, this case study uses the proposed framework to select the most valued material between the three most alternative floors in the Saudi residential villa (refer to the questionnaire section): Marble, Ceramic, and Porcelain. The following substeps are used in the case study.

3.4.1. Calculating Normalized QW and LCC. The proposed framework determines the eleven CWs for the flooring material (as shown in Table 7). In this step, the CQW numerical values for each criterion are determined through specific tests according to international standards, especially Saudi standards (SASO [29]). Accordingly, quality engineers with expertise in this field are consulted to classify these numerical values into three classifications in terms of quality: high, medium, and low. These classifications are converted to factors to facilitate the evaluation process. Subjective criteria are classified according to design professional expertise. Note that the durability criterion was measured based on the life expectancy of home flooring (Inter NACHI). The life expectancy of tiles is between 75 and 100 years, while Marble is 100+ years. Table 10 shows the CQW for the three-flooring material corresponding to the eleven flooring criteria. The normalized CQW value in Table 9 (the row below the CQW value initiated with letter “N”) is calculated using (4) and considers the optimal value test for each case study material. Using (4), QW for the three case study materials calculated by multiplying all the CW in Table 7 into CQW in Table 10 as the below:

QW (Ceramic) $= (0.44 \times 0.03) + (0.13 \times 0.04) + \ldots + (0.8 \times 0.16) = 0.64$.

QW (Porcelain) $= (0.7 \times 0.03) + (0.16 \times 0.04) + \ldots + (0.8 \times 0.8) = 0.67$.

QW (Italian Marble) $= (0.14 \times 0.03) + (0.23 \times 0.04) + \ldots + (0.8 \times 0.7) = 0.66$.

The case study cost data are shown in Table 11. M&R annual costs are 3% of the application’s initial cost [84].

Table 10: CQW for the case study.

Criteria		Modulus of rupture	Breaking strength	Surface hardness	Abrasion resistance	Water absorption	Coefficient of friction	Aesthetic	Durability	Maintainability	Thermal Conductivity	Buildability
Unit	Normalized (N) or value (V)	N/mm^2	N	Mohs	mm^3	%	μ	Subjective	Subjective	Subjective	W/m·K	Subjective
Alternatives		CQW according to international standards and experts										
The optimal reference values		50	8000	8	75	0.01	0.25	5	5	5	0.08	5
Ceramic (BIIa)	V	≥22	≥1000	≥5	345	≤6.5%	0.4	4	4	3.5	1.7	4
	N	0.44	0.13	0.63	0.22	0.002	0.63	0.8	0.8	0.7	0.05	0.8
Porcelain (BIa)	V	≥35	≥1300	≥5	175	≤0,5%	0.4	4	4	4	1.3	4
	N	0.7	0.16	0.63	0.43	0.02	0.63	0.8	0.8	0.8	0.06	0.8
Italian Marble	V	≥6.9	≥1850	≥4	250	≤0.10%	0.6	5	4.5	3	2.07	3.5
	N	0.14	0.23	0.5	0.3	0.1	0.42	1	0.9	0.6	0.04	0.7

Table 11: Normalized LCC values for the case study floor finishes.

Cost Unit	Initial Cost S.R/m^2	M&R Annual Cost S.R/m^2	LCC S.R/m^2	Normalized LCC Value
Porcelain	80	0.8	232.24	1103.15/232.24 = 0.21
Ceramic	65	0.65	188.7	1103.15/188.7 = 0.17
Marble	380	3.8	1103.15	1

According to the conditions of the Saudi Market, 1% of the initial cost has been considered in this study. The prices mentioned above and costs were obtained from the local Saudi market. Table 11 represents the Normalized LCC based on equation (4).

3.4.2. BIM Modeling and Calculate the Final Result. All the three selected floor finishes are modeled in the Revit model. Also, all CW and LCC values were entered (as calculated before using Tables 7, 10, and 11). They were entered promptly using Dynamo (as mentioned before) by importing them from the Excel sheet. Figure 5 shows one of the entry windows for the material. Subsequently, getting all QW and LCC values of three case study flooring materials, the V value for each of three material alternatives is calculated according to equation (7) as shown in Table 12 (column titled with "Value") from the highest alternatives to the lowest value. It also shows all the other material criteria values. The first best option is Ceramic and then Porcelain, characterized by quality standards nearly close in value. However, the cost criterion for Ceramic is better than the cost criterion for Porcelain and Marble. At the same time, the Marble has a higher aesthetic, less water absorption, and higher breaking strength.

3.4.3. Case Study Discussion. The result of this case study of choosing the Ceramic based on the VE concept is compatible with a case study done by Labuan and Waty [85]. In their study of flooring material in a two-story housing project in Indonesia, the ceramic flooring materials received a score of 32.1% as the highest percentage among the other ten flooring materials used in this study. The study used the probabilities technique with AHP and FAST methods to apply Expert Choice. Lee [10] attempts to develop a cost-effective evaluation of composite building materials such as flooring and wall system in other country studies. The study used two types of flooring systems (including the building slab concrete and insulation) in a Korean apartment to be evaluated. In another study, Lee [86] proposed a model for indexing the function, cost, and value scores using the vector normalization method. This model is applied to a case study of the office floor building to select its finishing materials.

This study used a typical housing building function weight to calculate the CW's. However, if the owner has a significate preference or needs regarding the type of flooring, the CW's values can be changed accordingly. Thus, the introduced framework gives a general guideline to building designers and needs to be updated to generate all types of buildings such as office, hospitality, healthcare, and others. Another flooring condition is exposing the floor to external weather, not transmitting electricity, minimizing sports injury, minimizing slipping near wet areas, and so on. Accordingly, further study is needed to develop the CW that satisfies the building function and performance. This model assumed all the nominated, evaluated alternatives are approved by the minimum acceptance designs of flooring materials for specific requirements such as having outdoor flooring, owner preference, or meeting minimum country specification (such as ISO or SASO). Future studies could eliminate these materials within the BIM model to meet the minimum accepted specification.

3.5. Phase 5: Framework Validation and Questionnaires. In this study, two questionnaires were designed. The first questionnaire is the experts' questionnaire; it is distributed to nine experts (three quality engineers, three consultants, and three designers), and the second one is the main questionnaire. Table 13 below includes a summary of details about the questionnaires.

The experts' and general questionnaires are designed using a Likert scale (Questions in Closed Ended Format) that required a ranking from 1 to 5. The questions analyzed based on 1 are the "lowest scale," and 5 is the "largest scale." The Score of each cause and effect can be calculated by using the Likert scale [87] weighted points shown in the following equations:

$$\text{Score } = \frac{\text{Total Likert points}}{\text{Total number of responders}}, \tag{8}$$

$$\text{Score} = \frac{1}{N} \sum_{i=1}^{5} i * ni. \tag{9}$$

where i is the Likert scale ($i = 1, 2, \ldots, 5$), ni is the number of responders who ticked scale i, and N is the total number of responders. A value is equal to or greater than four would be considered by this method.

3.5.1. Experts Questionnaire Results. Three specialized experts in the field were consulted, three professional and qualified architectural designers, and three expert consultants in stages for the research's reliability and verification during this study. Table 14 represents the results of the first question experts were asked for the most effective criteria for selecting floor finishing materials. These criteria are related to the necessary design considerations that assist in selecting materials for floor finishing.

Table 15 represents the questionnaire results of asking experts about the most important considerations for the designer to respond to the owner's needs and achieve its

Table 12: The Results of the Evaluation from the case study BIM model.

01 selection of floor finishes															
Type	Value	LLC_Cost	Normalized_Cost	Normalized_Quality	CR.01. Modulus_of_Rupture	CR.02. Breaking_Strength	CR.03. Surface_Hardness	CR.04. Abrasion_Resistance	CR.05. Water_Absorption	CR.06. Coefficient_of_Friction	CR.07. Aesthetic	CR.08. Durability	CR.09. Maintainability	CR.10. Thermal_Conductivity	CR.11. Buildability
Porcelain	3.2	232	0.21	0.67	35	1300	5	175	0.5	0.4	4	4	4	1.3	4
Ceramic	3.8	189	0.17	0.64	22	1000	5	345	6.5	0.4	4	4	3.5	1.7	4
Marble	0.66	1103	1.00	0.66	6.9	1850	4	250	0.10	0.6	5	4.5	3	2.07	3.5

Table 13: Summary of the framework questionnaires.

Questionnaire category	Respondents	Objective
Experts	9	Verify the common and most influential evaluation criteria (eleven predominant criteria) in selecting floor finishing materials. Verify a list of the designer's essential design considerations that aid experts in choosing the floor finishing materials to achieve the desired function of their design. Validate the optimum CQW value (Satisfaction Percentage). Validate the proposed framework (Satisfaction Percentage).
General	80	Verify the common flooring types used in residential buildings in Saudi Arabia to be used in the case study (Satisfaction Percentage). Validate the predominant eleven criteria in choosing floor finishing materials (Satisfaction Percentage).

Table 14: Expert Questionnaire verification about selection criteria of floor finishing materials.

		Frequencies							
No	The most common and influential evaluation criteria in the selection of buildings floor finishing materials	1 strongly disagree	2 disagree	3 neither agree nor disagree	4 agree	5 strongly agree	Total	Total likert –points	Select score ≥ 4
1	Fire Reaction		1	2	5	1	33	3.6	
2	Coefficient of Friction				3	6	42	4.6	✓
3	Colour Fastness		1	6		2	30	3.3	
4	Breaking Strength			1	5	3	38	4.2	✓
5	Surface Hardness			1	3	5	40	4.4	✓
6	Stain Resistance		1	7	1		27	3	
7	Frost Resistance		4	3		2	30	3.3	
8	Water Absorption		1		1	7	41	4.5	✓
9	Slip Resistance			4	3	2	34	3.7	
10	Thermal Conductivity			2	1	6	40	4.4	✓
11	Compressive Strength		2	1	3	3	34	3.7	
12	Chemical Resistance		2	3	2	2	31	3.4	
13	Dimensional Stability			7	2		29	3.2	
14	Abrasion Resistance					9	45	5	✓
15	Modulus of Rupture			1	6	2	37	4.1	✓
16	Thermal Shock Resistance			5	3	1	32	3.5	
17	Crazing Resistance		1	7		1	28	3.1	
18	Maintainability			1	3	5	40	4.4	✓
19	Durability				1	8	44	4.8	✓
20	Buildability				5	4	40	4.4	✓
21	Aesthetic				2	7	43	4.7	✓

desired function. The results indicate that the most five considerations are Resists Threats, Uses Safely, Attracts Customers, Performs the desired function, and Eases the Construction.

In addition, the experts validate the optimum reference value recorded for CQW. Table 16 represents the satisfaction results for each criterion's optimum reference value.

3.5.2. General Questionnaire Results. The general questionnaire seeks professional personnel working in the field of construction in Saudi Arabia. This questionnaire has been achieved according to the following three parts:

(1) Part One: Getting General Information about the Survey. This part was used to obtain information about the respondents. Seven hundred sixty-five persons received the questionnaire. The respondents' education distribution was as follows: 80 persons (10.45% of the total receivers), 4% of the respondents were with a Ph.D. degree, 34% were with a master's degree, 41% had a bachelor's degree. The respondents' backgrounds were mainly Architecture (53%) and Civil Engineering (34%). They have experience in various areas, Contractors (13%), Consultants (25%), Designers (34%), Client Representatives (5%), Academic Researchers (8%), and suppliers (16%). 38% of the participants have work experience of more than 15 years, 25% have experience ranging from 11 to 15 years, 13% have experience of 6–10 years, 9% have experience of 1–5 years. Figure 8 represents graphical distributional to questionnaire respondents.

(2) Part Two: Determine the Commonly Flooring Residential Types used in Saudi Buildings. The questionnaire participants were asked about the flooring types commonly used in residential buildings in Saudi Arabia. The questionnaire results in Table 17 showed that Marble, Ceramic, and

Table 15: Expert Questionnaire verification for important design consideration.

		Frequencies							
No	The most common and influential evaluation criteria in the selection of buildings floor finishing materials	1 strongly disagree	2 disagree	3 neither agree nor disagree	4 agree	5 strongly agree	Total	Total likert –points	Select score ≥ 4
1	Uses Safely								✓
2	Facilitate the operation		1	4	5		34	3.8	
3	Performs the desired function			1	5	3	38	4.2	✓
4	Resists Threats								✓
5	Attracts Customers					9	45	5	✓
6	Improve the Environment		2	4	3		28	3.1	
7	Ease of Construction			1	3	5	40	4.4	✓

Table 16: The percentage of satisfaction with the optimal values of CQW.

Criteria	Unit	The optimum reference value	Satisfaction percentage (%)
Modulus of Rupture	N/mm^2	50	93
Breaking Strength	N	8000	100
Surface Hardness	Mohs	8	100
Abrasion Resistance	mm^3	75	91
Water Absorption	%	0.01	98
Coefficient of Friction	μ	0.25	95
Aesthetic	None	5	100
Durability	None	5	100
Maintainability	None	5	100
Buildability	None	5	100
Thermal conductivity	W/m·k	0.08	97

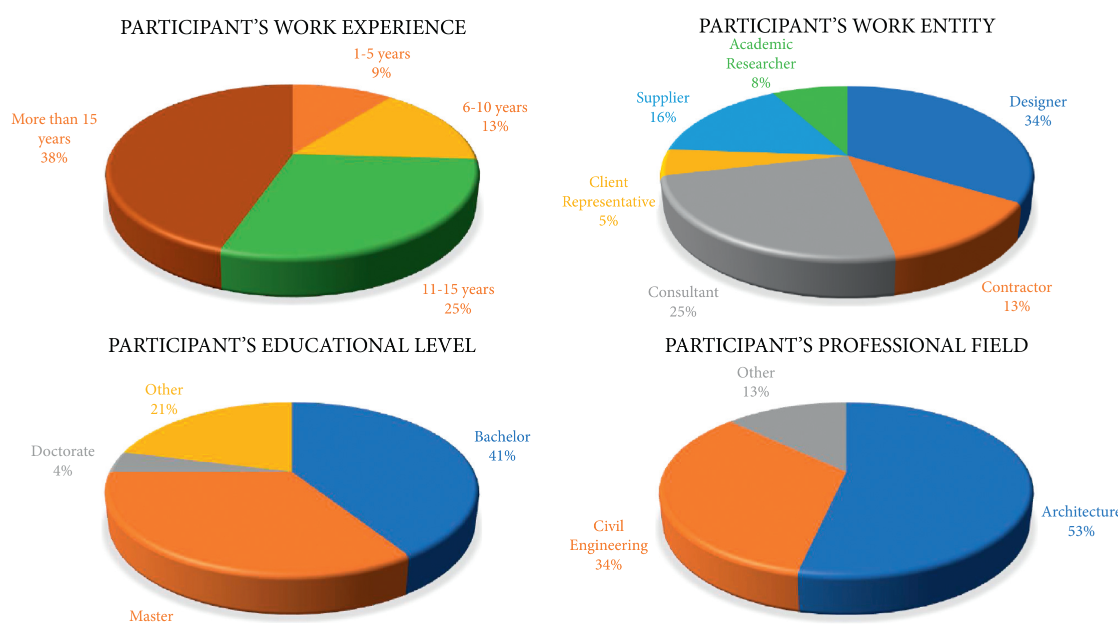

Figure 8: Distribution of Survey Participants' information.

Porcelain flooring are the most common types of flooring used in residential buildings in the Kingdom of Saudi Arabia. The results in this part were used in the previous case study.

(3) Part Three: Validate the Predetermined Eleven Criteria in Choosing Floor Finishing Materials (Satisfaction Percentage). The participants were asked about their satisfaction with the results of the experts' questionnaire on the common criteria

Table 17: Results of the general questionnaire–Part 2.

No	Flooring types are commonly used in residential buildings in Saudi Arabia	Frequencies							
		1 strongly disagree	2 disagree	3 neither agree nor disagree	4 agree	5 strongly agree	Total	Total likert-points	Select Score ≥ 4
1	Parquet	27	19	21	9	4	184	2.3	
2	Carpet	14	23	25	10	8	215	2.7	
3	Ceramic	2	5	14	22	37	327	4.09	✓
4	Granit	27	36	5	9	3	165	2.06	
5	Vinyl	14	18	13	20	15	244	3.05	
6	Marble		7	10	29	34	330	4.13	✓
7	Porcelain		4	7	39	30	335	4.2	✓

Table 18: Results of general questionnaire–Part 3.

The Most common criteria affecting the quality of finishing materials floors	Agree (%)	Disagree (%)
Modulus of Rupture	89	11
Breaking Strength	81	19
Surface Hardness	86	18
Abrasion Resistance	80	20
Water Absorption	100	0
Coefficient of Friction	95	5
Aesthetic	99	1
Durability	93	7
Maintainability	94	6
Thermal Conductivity	91	9
Buildability	93	7

Table 19: Experts satisfaction for the framework.

No	Data	Experts' satisfaction (%)
1	Criteria Weights (CW) Values	80
2	Quality Weights (QW) Values	87
3	Life Cycle Cost (LCC) Values	93
4	Overall Value Results	87

that most influenced the process of selecting floor finishing materials. The results are shown in Table 18. The results of this part are used to validate the framework criteria.

3.5.3. Validate the Proposed Framework. The case study results were presented to the same nine specialized experts consulted in the expert questionnaire to validate the research's final results. They were asked to express their satisfaction degree on a *Likert Scale* about the quality values, cost values, the criteria weights, and the overall value results. Their response is summarized in Table 19.

The expert's opinions prove that the proposed framework gives reliable results that can be adopted for materials evaluation.

4. Conclusion

This study suggested an automated BIM framework for selecting floor finishing materials. Eleven criteria for selecting flooring finishing are identified by searching several references and material standards and catalogs. They are also validated by interviewing three strong backgrounds in flooring quality. Seven common and agreed standard tests are identified to measure the flooring quality criteria from these eleven criteria. Also, four subjective selection criteria have been evaluated within the framework. Table 1 represents these eleven criteria. These selection criteria are weighted by conducting interviews with three experts. The weighting methodology links these criteria with building function and integrates AHP, FAST, and pairwise methods. These weighted criteria become a basis for measuring any flooring finishing material. Moreover, the framework has been integrated with BIM using API Application and Dynamo.

A case study of a residential building is utilized to demonstrate the proposed automated framework. The case study shows the incorrect perception that not all materials with good quality are selected, but their cost has to be considered along with quality. Lastly, three experts' opinions are conducted to validate the proposed framework. Expert engineers evaluated the value of cost and quality, overall value results, and criteria weight. The proposed framework was validated as 85% satisfaction by the experts.

Because of having various market options, selecting and evaluating the finishing flooring materials is considered a complicated process. Thus, VE is difficult to apply in such a task because of having variations in flooring material standard tests, selection criteria, LCC, and the building's needs and function. As a result, the VE process becomes more dependent on the expert's knowledge and does not follow a systematic approach that can be automated. In general, the proposed automated framework is a valuable tool to respond to such issues. It assists the designers/owners in selecting the most efficient finishing flooring materials. The residential case study result demonstrates a helpful general guideline tool to the designer/owner in reaching the right decision in a short time. Moreover, the framework simplifies the time-consuming process of comparing numerous flooring material specifications to judge the material quality and measure it. Nevertheless, the framework can be developed more comprehensively for all building functions and performance.

Abbreviations

AEC: Architecture, Engineering, and Construction industry
AHP: Analytic Hierarchy Process
ASTM: American Society for Testing and Materials
BIM: Building Information Modeling
CQW: Criteria Quality Weight
CW: Criteria Weight
DSS: Decision Support Systems
EN: European Standards
FARE: Factor relationship
FAST: Function Analysis System Technique
HVAC: Heating, Ventilation, and Air Conditioning
ISO: International Organization for Standardization
LCC: Life cycle cost
LSTMM: Linear Scale Transformation Max Method
MCDM: Multi-Criteria Decision-Making
OSM: Optimal Scoring Method
QW: Quality Weight
SASO: Saudi Standards, Metrology, and Quality Organization
TOPSIS: Technique for Order Preference by Similarity to Ideal Solution
V: Material Value Ratio
VE: Value Engineering
WASPAS: Weighted Aggregated Sum Product Assessment method.

Data Availability

Different research papers and journals were used to produce this paper using common academic databases and search engines. Therefore, raw data supporting the findings of this paper will be available by the corresponding author on request.

Conflicts of Interest

No conflicts of interest exist.

Acknowledgments

The author would like to thank the Deanship of Scientific Research (DSR), the King Saud University (KSU), for supporting this research through the initiative of DSR Graduate Students Research Support (GSR). Also, the authors would like to thank the Saudi Standards Metrology and Quality Organization (SASO) for their support. Moreover, the authors would like to thank all participants for verifying and validating this study. The author would like to thank the Deanship of Scientific Research (DSR), King Saud University (KSU), for supporting and funding this research.

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