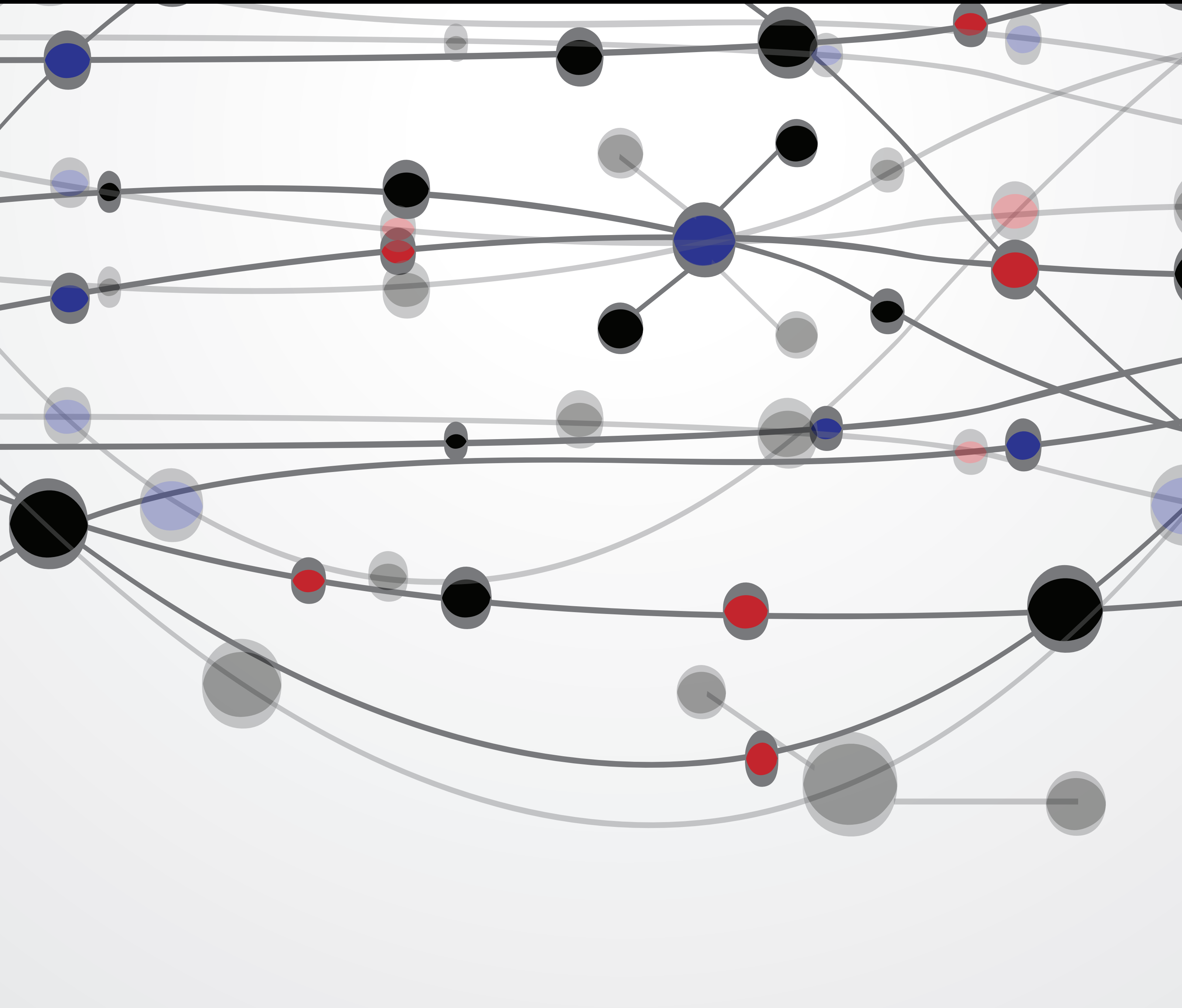
The Scientific World Journal

Recent Advances on Building Information Modeling

Guest Editors: Yu-Shen Liu, Heng Li, Haijiang Li, Pieter Pauwels, and Jakob Beetz



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Editorial

Recent Advances on Building Information Modeling

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Building information modeling (BIM) technology has been receiving an increasing attention in the architecture, engineering, and construction (AEC) industry. Unlike traditional computer aided design (CAD) technology, BIM technology allows storing both geometric information and rich semantic information of building models, as well as their relationships, to support lifecycle data sharing. In terms of information technology (IT) adoption, BIM is a new trend in the AEC industry. However, BIM still suffers from lack of fundamental research, such as the representation, exchange, and interoperability of information. In addition, research on various BIM applications is also very prospective. These trends provide new challenges and opportunities for researchers.

This special issue aims to bring researchers from academia and industry together to report and explore new methodologies and applications in BIM and review the latest progress in this field. Out of about forty submissions, five research articles have been selected and included in this special issue due to their good quality and relevance to the theme. The selected papers address various aspects, including a translation approach between BIM and building energy modeling, a practical method with application to facility management (FM) using 2D barcodes and BIM technologies, a BIM-based virtual environment for fire emergency evacuation, a BIM data application to building performance simulation software for the early phases of building design, and a BIM-based approach in construction to support the construction procurement process.

The exchange of data between building design representations and energy simulation representation has been a major challenge in the design process, resulting in the fact that building energy performance simulation is often omitted from the process. The translation process is labor intensive, error-prone, and cumbersome. Although tools have been developed to support the generation of an energy model from a design model, disconnections still exist between the various models. In practice, many of the problems derive from building energy simulation tools that fail to take advantage of object-oriented programming (OOP) and do not easily allow for mapping from an object-oriented design model. To improve and enhance the model translation effectiveness, W. Jeong et al., in their paper titled "Translating Building Information Modeling to Building Energy Modeling Using Model View Definition", present a translation approach to translate between BIM and building energy modeling (BEM) that uses Modelica, an object-oriented declarative, equation-based simulation environment. A tool, named BIM2BEM, has been developed using a data modeling method to enable seamless model translations of building geometry, materials, and topology. Using data modeling, the authors created a model view definition (MVD) consisting of a process model and a class diagram. The process model demonstrates object mapping between BIM and Modelica-based BEM (ModelicaBEM) and facilitates the definition of required information during model translations. The class diagram represents the information and object relationships to produce a class package intermediate between the BIM and BEM. The implementation of the intermediate class package enables system interface (Revit2Modelica) development for automatic BIM data translation into ModelicaBEM. In order to demonstrate and validate the approach, simulation result comparisons have been conducted via several test cases.

Facility management (FM) has become an important topic in research on the operation and maintenance phase. Effectively managing a facility is extremely difficult owing to the variety of environments. One of the difficulties is the performance of two-dimensional (2D) graphics when depicting facilities. BIM uses precise geometry and relevant data to support the facilities depicted in 3D object-oriented CAD. To address this issue, Y.-C. Lin et al., in their paper titled "Developing Mobile BIM/2D Barcode-Based Automated Facility Management System," propose a practical method with application to FM that uses an integrated 2D barcode and the BIM approach. Using a 2D barcode and BIM technologies, this study proposes a mobile automated BIM-based facility management (BIMFM) system for FM staff in the operation and maintenance phase. The mobile automated BIMFM system is then applied in a selected case study of a commercial building project in Taiwan to verify the proposed methodology and demonstrate its effectiveness in practice. The combined results demonstrate that a BIMFM-like system can be an effective mobile automated FM tool. The advantage of the mobile automated BIMFM system lies not only in improving efficiency for the FM staff but also in facilitating FM updates and transfers back into the BIM environment.

Recent building emergency management research has highlighted the need for the effective utilization of dynamically changing building information. BIM can play a significant role in this process due to its comprehensive and standardized data format and integrated process. To address this issue, B. Wang et al., in their paper titled "BIM Based Virtual Environment for Fire Emergency Evacuation," introduced a BIM-based virtual environment supported by virtual reality (VR) and a game engine to address several key issues for building emergency management, for example, timely two-way information updating and better emergency awareness training. The focus of this paper lies on how to utilize BIM as a comprehensive building information provider to work with VR technologies to build an adaptable immersive serious game environment to provide real-time fire evacuation guidance. The innovation lies in the seamless integration between BIM and a VR environment, thereby aiming at practical problem solving by leveraging state-of-the-art computing technologies. The system has been tested for its robustness and functionality against the development requirements, and the results show promising potential to support more effective emergency management.

Data mining techniques are not often used in combination with building information modeling (BIM) technology. Nevertheless, applying data mining techniques on a database of BIM models could provide valuable insights in key design patterns implicitly present in these BIM models. The architectural designer would then be able to use previous data from existing building projects as default values in building performance simulation software for the early phases of building design. K. Hiyama, in the paper titled "Assigning Robust Default Values in Building Performance Simulation Software for Improved Decision-Making in the Initial Stages of Building Design," proposed a method to minimize the magnitude of variation in these default values in subsequent design stages. This approach maintains the accuracy of the simulation results in the initial stages of building design. In this study, an argument is presented to demonstrate the significance of the new method. The variation in the ideal default values for different building design conditions is assessed first. Next, the influence of each condition on these variations is investigated. The space depth is found to have a large impact on the ideal default value of the window-to-wall ratio, whereas the window orientation has little impact. In addition, the presence or absence of lighting control and natural ventilation has a significant influence on the ideal default value. These effects can be used to identify the types of building conditions that should be considered to determine ideal default values for a new building design project.

Finally, A. A. Costa and A. Grilo, in their paper titled "BIM-Based E-Procurement: An Innovative Approach to Construction E-Procurement," describe a particular BIM application with an approach to e-procurement in construction, which uses BIM to support the construction procurement process. The result is an integrated and electronic instrument connected to a rich knowledge base capable of advanced operations and able to strengthen transaction relationships and collaboration throughout the supply chain. The BIM-based e-procurement prototype has been developed using distinct existing electronic solutions and an IFC server and was tested in a pilot case study, which supported further discussions of the results of the research.

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Research Article

BIM-Based E-Procurement: An Innovative Approach to Construction E-Procurement

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This paper presents an innovative approach to e-procurement in construction, which uses building information models (BIM) to support the construction procurement process. The result is an integrated and electronic instrument connected to a rich knowledge base capable of advanced operations and able to strengthen transaction relationships and collaboration throughout the supply chain. The BIM-based e-procurement prototype has been developed using distinct existing electronic solutions and an IFC server and was tested in a pilot case study, which supported further discussions of the results of the research.

1. Introduction

In the last few years, as an answer to the increasing need to reduce waste and improve performance, several innovative technologies emerged in the construction sector. New information and communication technologies (ICT) have challenged traditional working methods and stimulated change and modernization, especially in areas of e-business and building information modelling (BIM) [1–8]. Slowly but progressively, these technologies are being integrated into construction processes, demonstrating the prospect of potential gains.

E-business platforms, which may take different forms [9, 10], play an important role as communication and business process management instruments, emerging as an effective support to collaboration, information management, and sharing [11, 12]. The extranets supported by these electronic platforms capture the supply chain communication practices and provide controlled communication, and the relevance of information sharing instruments is becoming progressively evident for the industry [13]. The automated business processes supported by these platforms allow for increasing process efficiency and project management capabilities and leverage the role of information during projects' lifecycles, creating an information-based environment that improves BIM potential and stimulates its implementation. Subsequently, the implementation of BIM emphasizes knowledge sharing throughout the life cycle of a building, making supply chain and life cycle integration possible and improving information management capabilities [14].

Considering these emerging issues, we propose an innovative approach to e-procurement in construction that uses BIM to support e-procurement processes. The hypothesis behind the proposed framework is that BIM-based solutions may reduce the negative effects of the fragmentation of the construction project lifecycle through the integration and integrity of information across the procurement processes in a project's life-cycle. This will imply new strategic approaches to the procurement cycle and support more accurate decisions. The result is an integrated instrument connected to a rich knowledge base capable of advanced operations and able to strengthen transaction relationships and collaboration throughout the supply chain.

In order to achieve this purpose, the paper starts by reviewing the literature regarding e-procurement and BIM, focusing on major developments and most significant impacts on the construction industry. The paper then presents a BIM-based e-procurement model and respective prototype, which was developed to test the validity of the formulated model. Finally, the paper discusses the application of the prototype to a pilot case study, reporting the most important results of the research.

2. E-Procurement and Building Information Modelling in the AEC Sector

2.1. Developments in E-Procurement in the AEC Sector. According to several authors [15, 16] the use of e-procurement platforms results in a reduction of more than 3% of public expenditures without reduction in outputs. This is possible mostly because e-procurement helps to reduce complexity, improves competitiveness and transparency, and creates an integrated electronic environment to support advanced electronic instruments to manage, and monitor contracts [17].

E-procurement is best viewed broadly as an end-to-end solution, which integrates and streamlines many procurement processes throughout an organization [18]. Some of these procurement processes are the following:

(i) ex-ante e-evaluation: refers to multicriteria evaluation of needs and procurement strategies;

(ii) e-noticing: concerning electronic publication of public procurement notices;

(iii) e-submission: concerning electronic submission of proposals;

(iv) e-decision: concerning electronic evaluation of proposals, subsequent communication of evaluation results, and discussion and analysis of results;

(v) e-award: concerning electronic contract awards to suppliers with the best proposals;

(vi) e-ordering: concerning all activities, including sending an order document from public buyers to suppliers, to the transmission of delivery instructions for ordered goods and services;

(vii) e-invoicing: concerning claim for payment for goods and services ordered and delivered under agreed-upon conditions;

(viii) e-payment: agreed electronic payment management and execution;

(ix) e-contract management: refers to the use of electronic contract management instruments to monitor and improve contract performance and document management;

(x) ex-post e-evaluation: agreed multicriteria evaluation of the contract execution, and the eventual generation of KPIs to support future tendering processes.

In a fully integrated and paperless context, all these processes should be combined and all relevant information must be available electronically. This will allow for a reduction of administrative work and automate operational processes, offering more time to think strategically [19]. On the other hand, it will accelerate market information efficiency, allowing further fine-tuning of procurement decisions such as supplier and proposal evaluations, procurement methods, and negotiation strategies [20].

Considering its advantages, several countries are encouraging the implementation of e-procurement in the public sector [21]. For instance, in Portugal the Public Contracts Code (PCC) was approved by Decree-Law 18/2008 on January 29, 2008, and is in force since July 29, 2008, mandates public e-procurement in Portugal. Currently, public procurement is completely paperless and, gradually, the private sector is recognizing its advantages and implementing e-procurement, especially in the construction sector [17]. This situation raises interesting opportunities for e-procurement service providers and offers an important incentive to construction since it pushes firms and public authorities to modernize and digitalize, obligating the implementation of more responsive, collaborative, and intelligent working systems. Inevitably, the competitive environment around e-procurement service providers stimulates the development of more advanced e-procurement solutions, which integrate not only the entire e-procurement cycle but also the project lifecycles and provide support for innovative procurement and working models [22].

Against the technological potential of the existing electronic instruments, strategic perspectives on procurement and more integrated approaches to supply chains gain momentum and the integration of e-procurement with other industry-oriented ICT, such as BIM, becomes extremely important. The present research reflects this progressively paperless environment and effectively integrates these relevant technologies that are changing the construction paradigm.

2.2. Building Information Modelling. BIM has been developed in the last decade with the advent of refined computer aided design (CAD) systems able to enrich virtual 3D models of buildings with complementary data (as physical characteristics, unit costs, fabrication details, etc.). As a new methodology, BIM promotes a more cooperative work between all specialties during the different stages of the construction project and also used during the life cycle of the building allowing a more efficient use of resources, decrease of errors due to lack of information/communication, and a more efficient management of the building operations costs [6, 23, 24].

Increasing use of BIM has been seen in the last few years [25, 26]. This is mostly due to the potential of this technology to improve construction project performance becoming more widely recognized. Eastman et al. [6] argue that BIM technology makes it possible to construct an accurate 3D virtual and parametric model of a building containing precise geometry and relevant data needed to support construction, fabrication, and procurement activities necessary for the building process, which effectively contributes to increase collaboration and project quality. Thorpe et al. [27] also emphasize that by making virtual reality simulations possible, BIM fosters project understanding and emphasizes integrated and coordinated decision-making in supply chains, providing the construction industry with an instrument to support more rigorous and consistent decisions throughout the building's life cycle. It is worth mentioning that several case studies demonstrating effective performance improvements can already be found in the literature [28–31].

Several authors point out that the true benefits of BIM are obtained when the technology is applied throughout the project lifecycle, from design to demolition [32]. However, this leads to a major challenge: the data exchange between all the parties demands seamless interoperability [24, 33]. Efforts to address this problem have been undertaken, mainly related to the development of standard formats, such as the industry foundation classes (IFC) [34, 35]. IFC is an object-oriented interoperable format for representing building product model data and may be the most used format for interoperability purposes.

The construction industry is gradually starting to understand the importance of interoperability in order to achieve integrated and automated work processes, with savings in cost and time [36]. As more disciplines of the construction industry adopt building information modeling, integrated design, and delivery work processes, the need for interoperable applications grows clearer [37]. Lipman et al. observe that industry leaders and government agencies now recognize the importance of addressing the interoperability problem, and numerous reports document the imperative to solve this problem. The National Research Council report [38] on the competitiveness and efficiency of US construction, for example, clearly states that the lack of interoperability is a major source of construction industry waste and inefficiency.

In an interoperable scenario, BIM is a powerful tool to support lifecycle integration [39] and in the particular case described in this paper, to support the e-procurement process. The information contained in the BIM-based design model can be shared directly in an e-procurement process, which can reduce the heavy human workload and manual errors in traditional work. Due to the complexity of construction, e-procurement processes are still time-consuming and prone to error [3].

Having all the information centralized in a specific model may increase process efficiency and accurateness. As Ma et al. [36] mention, highlighting the case of cost estimation, several BIM-based software applications have emerged, such as Innovaya [9] and Vico Estimator [10], in which the BIM-based design model can be imported to perform effective tendering of building projects cost estimation, confirming that the use of BIM throughout the procurement process may realize considerable gains.

In a paperless, interoperable, and information-based environment such as the one encouraged by the use of BIM, interesting synergies can be generated by combining BIM with other ICT, such as e-business platforms. This combination results in hybrid electronic platforms capable of several advanced operations. Asite [40] is an example of these hybrid platforms. In this case, a document and model management instrument are connected to a BIM server, improving information management capabilities. Onuma [41] should also be cited as another type of hybrid platform. In this case, it is a web-based planning system supported by a model based platform essentially oriented to the conception and design construction phase. Although these cases demonstrate that interesting results can be achieved with this hybrid approach, few solutions exist, especially using open formats, such as IFC, and few efforts have yet been made to explore some specific functions, such as the application of BIM for e-procurement. This specific application may be achieved in the near future, however, as BIM is becoming mandatory for public works in several countries, and this specific application may help to leverage construction procurement performance, particularly by emphasizing the role of information throughout the procurement cycle and, mostly, by allowing the automation of several procurement processes, diminishing the probability of errors and processes duration.

3. Research Method

The present study was developed as an action research [42] conducted within a business environment, presupposing strong commitment between team members [43]. The research team included members from the following:

(i) two universities, mainly responsible for the coordination and development of the scientific work;

(ii) an e-procurement service provider that provided the e-procurement platform and respective web services;

(iii) a software house specialized in project management software applications, which provided support on project management features;

(iv) a network of construction partners who gave important feedback on the project and participated in the simulation test.

All participants gave rich, full insights and participated proactively. This participative and collaborative process were based on cycles, each of which comprised several steps: planning, action, and fact-finding about the result of the action. These cycles converged on better understanding the problems and phenomena throughout a learning process based on continuous refinement of methods, data, and interpretation [44]. In the case of the research reported here, the research cycles focused on three major phases:

(i) exploratory study and proposition of a BIM-based e-procurement framework;

(ii) development of a prototype of the solution proposed;

(iii) simulation and test of the prototype developed using a pilot case study, an experiment with a fixed approach, and a controllable environment.

In the following sections, the most important developments and outcomes achieved during the three major phases of the research are presented, with special attention to the critical issues faced.

4. BIM-Based E-Procurement Framework

Joining developments in ICT and procurement in the AEC sector, the authors consider that a BIM-based e-procurement

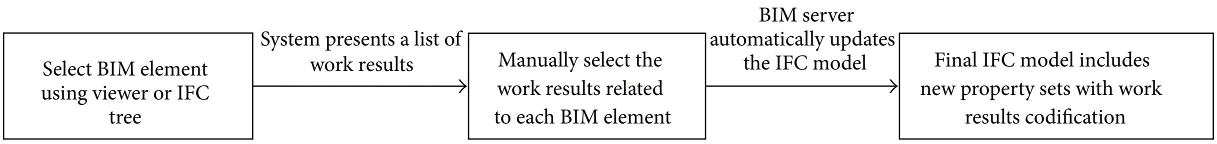


FIGURE 1: Method to include in the BIM model additional information (such as work results).

FIGURE 2: Method to initiate procurement process using BIM model.

solution not only makes more advanced and intelligent approaches to e-procurement systems possible but also promotes the generation of large electronic and interoperable networks that interact dynamically. The rich information-based environment that is thus created not only strengthens the automation of many operational tasks but also enhances information and knowledge management. This supports more accurate decisions and strategic approaches to the procurement cycle and potentiates more effective collaborative planning, collaborative design, integrated decision, scenario analysis, product comparison, document automation, processes automation, contract management, and performance management. This shifts from traditional e-procurement approaches, where CAD files are exchanged but are mainly used by each agent to print and recreate their own information models, not reusing or integrating information and not contributing to reduce construction projects fragmentation, recognized as a major hindrance to increase construction productivity. With BIM-based e-procurement, information may indeed flow in a more seamless way across application of the various agents within procurement processes.

The proposed solution allows any user to initiate an e-tendering process using a BIM model. For instance, if a contractor wishes to purchase a specific product for a building, he can select that product (or related element) in the BIM model and launch the tendering process using the electronic platform. Automatically, all the necessary information is obtained from the model and the tendering is initiated.

It is important to note that the use of BIM for procurement purposes demands a very detailed model, including all necessary information to launch the tendering process, which is a major challenge. Every BIM element must include several information sets such as work results related to each element or product identification (or types of product) in order to allow for the implementation of automatic procurement procedures. The association of this information to BIM elements can be made using the method presented in Figure 1, which can be implemented by an electronic tool that presents a list of organized information related to relevant types of information (work results, products, or other) after the user selects a specific BIM element.

Although the links must be created manually using taxonomies available, information should be automatically included in the IFC model. To automate this operation the electronic platform should be connected to a BIM server, which should allow creating a new property set in the IFC file in which it includes the information previously associated with BIM elements. It is possible thereafter to initiate the e-procurement process in a simple way (Figure 2). Selecting the BIM element, it is also possible to send "requests for information" or "requests for quotes," which will guarantee that all information (including messages) are linked to the model. Tenderers may also submit tenders using the BIM model. In this sense they must attach specific information about the products, the costs, and the resources to the model. The process is similar to the one presented previously (Figure 3).

It is important to understand that some information is not easily included in the model. This makes it imperative that the system be able to attach files to elements of the BIM model. In this sense the system should create connections between messages and/or files and the elements of the BIM model. By selecting a determined BIM element (using the viewer of the IFC tree view, which is an hierarchic view of IFC elements), it should be possible to attach and access all the information related to it, not only information within the model but also external information connected to the model previously (messages, files, external links, etc.) [5]. This feature would allow procurers and tenderers to attach information to the model information that is not included in the BIM model.

5. BIM-Based E-Procurement Prototype

5.1. Use Cases and Front-End Development. The first step toward prototype development was to model traditional workflow for the construction e-procurement lifecycle, which included identifying the various players and respective value-added activities, information flows mapping, and determining major deliverables and decision points.

Providing a standard visualization mechanism for business processes defined in an execution-optimized business

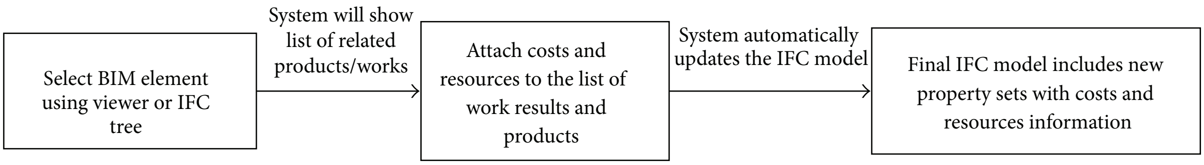


Figure 3: Method to make a proposal using the BIM model.

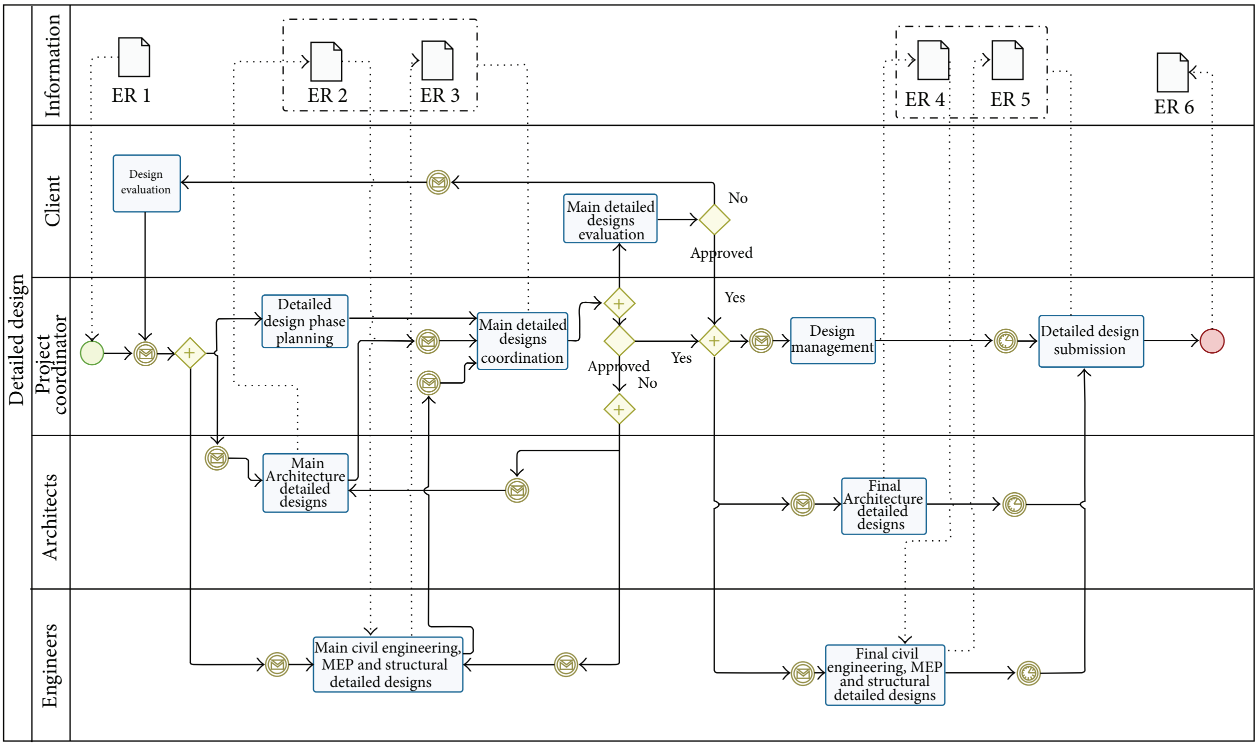


Figure 4: BMPN map example.

processing language [45], business process model and notation (BPMN) was used to model all traditional processes inherent to construction lifecycle phases (Figure 4) [46]. Special attention was paid to actors, major decisions taken, and information flows; the principal deliverables generated in each phase were also identified and described. Afterwards, BPMN diagrams were analyzed in detail and several modifications were introduced into the workflow to optimize information flows and enhance collaborative work, recurring to existing technologies such as BIM. Existing e-procurement platforms were the starting point for the developments proposed.

The resulting BPMN diagrams supported the development of a functional matrix in which the functionalities of the platform for each phase and each type of user were identified that considered information requirements identified previously. Considering the functional matrix and the BPMN diagrams, the use cases were then defined and, in accordance to use case specifications, front-ends were constructed. Microsoft SharePoint was the instrument used to implement them based on a form metaphor structure consisting of a series of forms (pages) with which the user interacts. Each form contained a number of fields that display output from lower layers and collect user input.

5.2. Platform Architecture. To support the BIM-base procurement framework previously described, the electronic platform (called PLAGE platform) was developed integrating and combining four different preexisting solutions. Microsoft SharePoint 2007 was used as the business collaboration platform system and as the front-end and to implement a set of workflow and rule-based procedures for the e-procurement. The EDM Model Server from Jotne EPM Technology was used to implement BIM-based features such as storing and manipulating IFC models. The IFC Engine Viewer provided by TNO was used as an IFC 3D viewer. Vortal eGOV is an e-procurement platform for the AEC sector. The IFC version considered was the IFC2x3 version.

The disparate electronic instruments work seamlessly in an integrated way through Web-services connections. The platform generic technology architecture was grounded on the combination of the latest architectures like model-driven architecture (MDA), the service-oriented architecture (SOA),

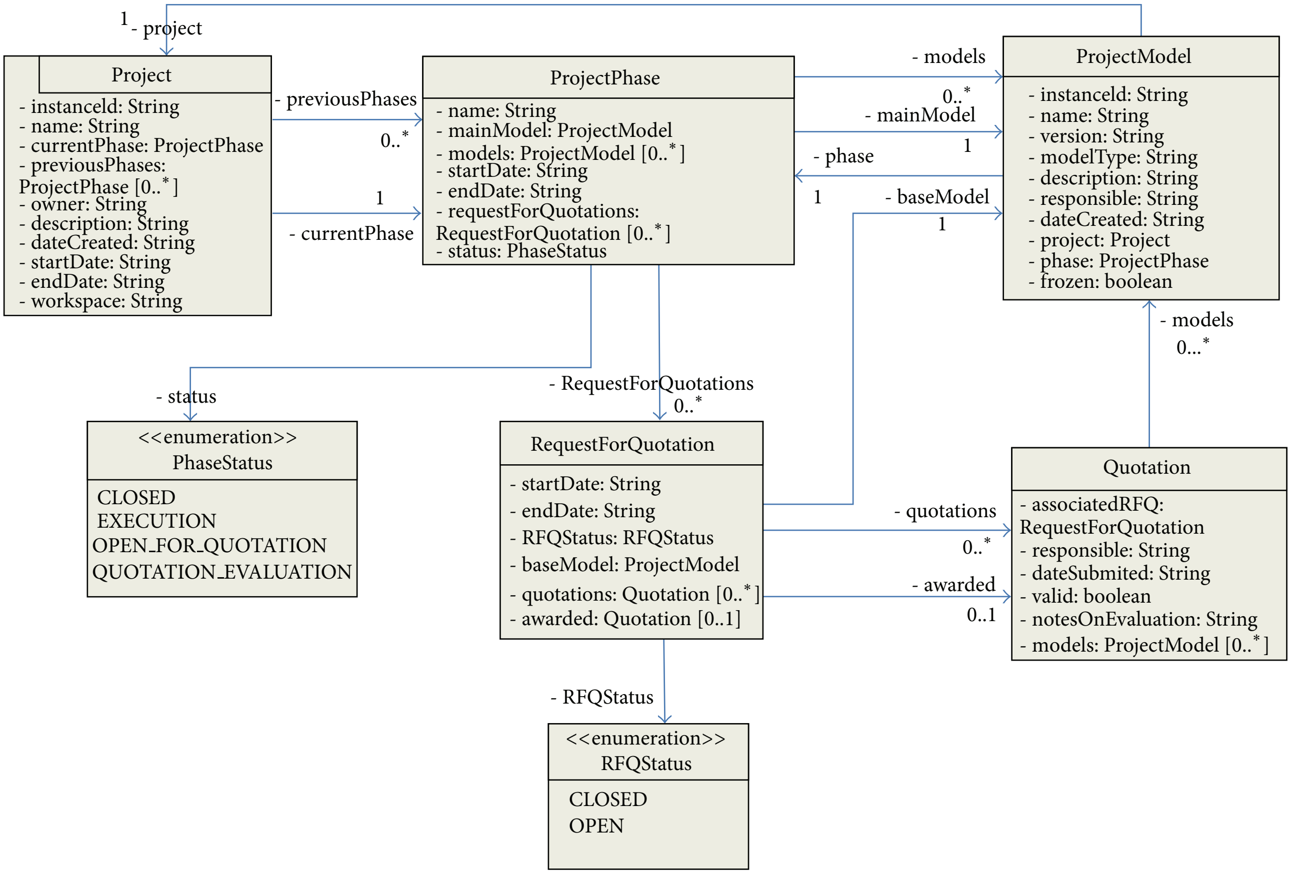


Figure 5: Information model implemented on the EDM server.

cloud computing, and building information model (BIM)—the SOA4BIM Framework [47–49]. The application of the SOA4BIM Framework in the context of e-procurement is expected to overcome many technological barriers by reusing much of the standardization and research work done in the BIM and AEC sector, namely, the IFC and STEP standards, and at the same time use current technology, like Web-services, for implementation. To structure the development of the platform, the service-oriented approach was organized into four layers [50]:

(i) *presentation layer*: providing the application user interface and involving forms for smart client interaction and ASP.NET technologies for browser-based interaction;

(ii) *application services layer*: implementing the business functionality of the application, comprising a number of components implemented using one or more NET programming languages;

(iii) *Business/interoperability services layer*: supporting business services connected with external services using SOAP;

(iv) *data layer*: providing access to external systems such as databases.

5.3. IFC Server Implementation. In the present case the EDM server component was used to perform IFC operations and the client application has been fully developed using Sharepoint framework. Considering the specific requirements of the research project, new information models have been designed and implemented on the EDM server in order to allow an efficient management of the project data (Figure 5) and define the information flow based on the IFC objects included in the IFC model (Figure 6). In this case, the entities are not persistent, and are used only to support information flow between the client and the server. For more information on these information models please see the appendix.

In order to link the BIM elements to the tasks, a connection between the EDM server and the software Primavera CCOP has been implemented using the web services. This allows the EDM server to send information to Primavera CCOP, which generates the list of elements based on the Uniformat standard and supports the manual linking of these elements to the respective work results.

5.4. BIM-Based Interface. The BIM-based interface was created according to the proposed solutions and supports two major advanced features:

(i) viewing and manipulating IFC models, providing access to all the information contained in the models (Figure 7);

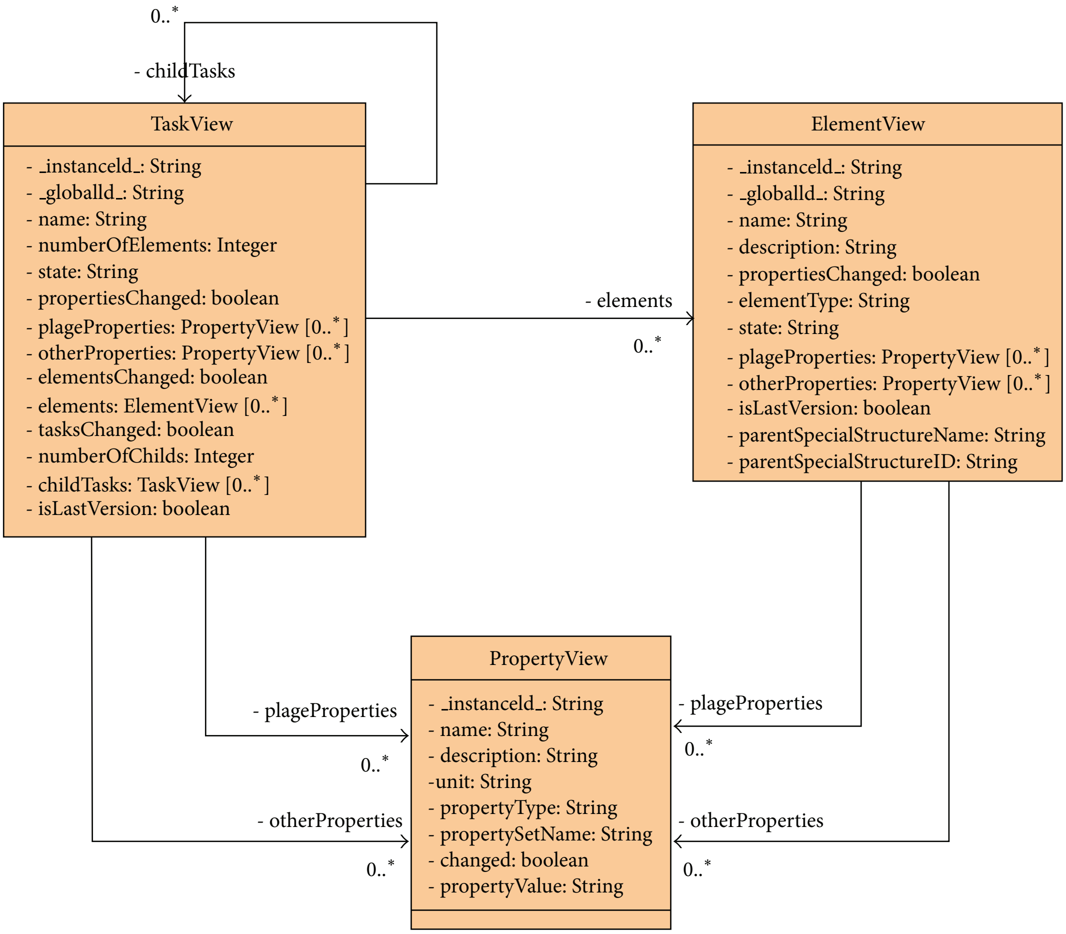


FIGURE 6: Information model to support client-server information flow.

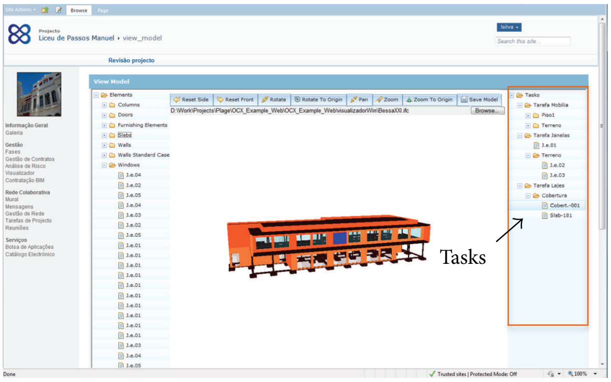


FIGURE 7: BIM viewer (IFC-based).

(ii) managing tasks and other information related to each BIM element, from which it is possible to initiate the e-procurement process using the connection implemented with the Vortal e-procurement platform.

As mentioned above, the IFC engine viewer used (provided by TNO) is an IFC viewer with an advanced content mapper based on internal queries, which allows visualizing and interacting with 3D models. It has been embedded in the platform as an applet and integrated in the platform information flows.

6. Pilot Case Study: Liceu Passos Manuel

The PLAGE platform prototype was tested using a pilot case study based on a public sector project focusing on the renovation and expansion of a public secondary school, the Liceu Passos Manuel. The public entity responsible for the work provided all necessary documentation, including detailed design, specifications, and contract, and interacted with the research team to explain the most important features of project design and construction. Several other entities, such as major contractors and designers, also provided useful insights to enrich the research study. Throughout the pilot case several issues were addressed regarding the implementation of the innovative BIM-based e-procurement solution developed.

To test the prototype, the design and a part of the procurement process inherent to the Liceu Passos Manuel school project were simulated. The pilot case was structured in 13 major steps, shown in Figure 8.

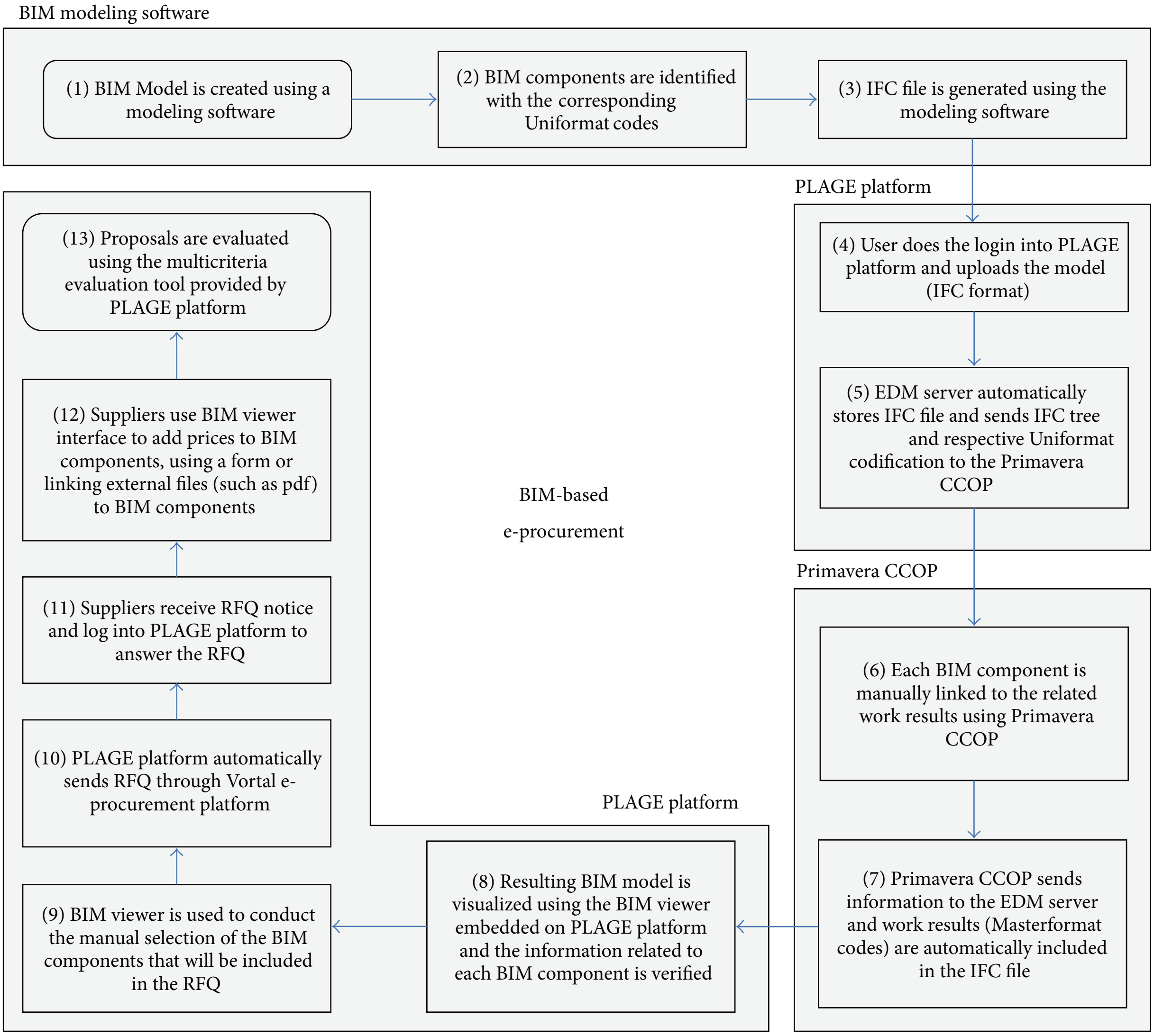


Figure 8: Simulation scenario.

Throughout these steps the BIM-based e-procurement prototype was tested in various ways, including the following:

(i) viewing and manipulating BIM models created throughout the pilot case and accessing inherent information;

(ii) using BIM model viewer to attach external files to the model;

(iii) launching RFQ and RFI (requests for information) using BIM-based e-procurement interface;

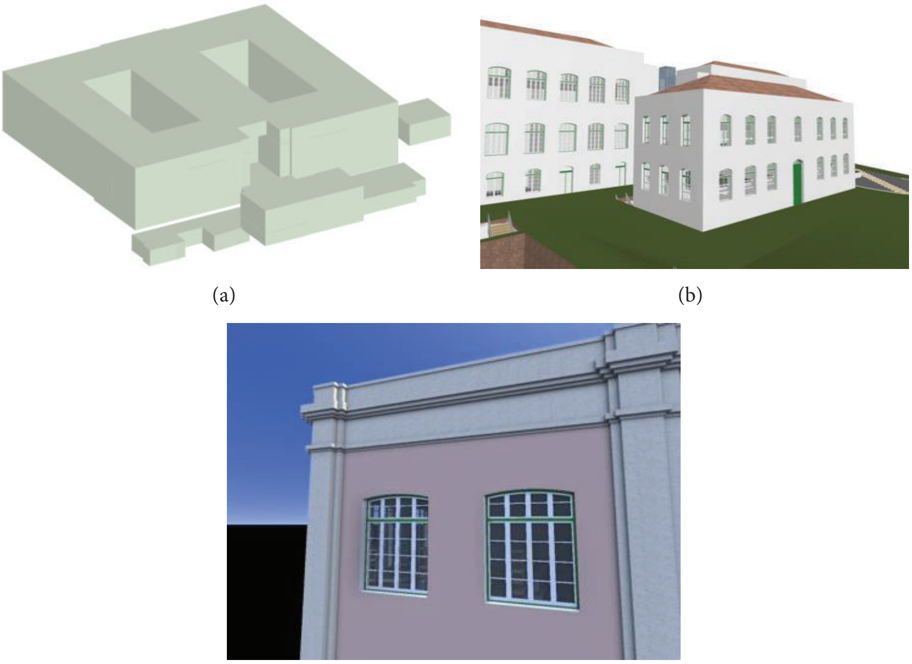
(iv) initiating e-procurement process based on the elements of the BIM model;

(v) submitting a proposal using the BIM-based interface.

A brief description of each step is presented below in order to clarify the entire pilot testing process.

Step 1. In this initial stage several BIM models have been created (the designs provided were in 2D), which were used to test consistency of the BIM-based interface and PLAGE BIM management module. The modeling process reflects four modeling steps with increasing design detail and follows the BIM directives adopted in other countries (Figure 9), such as the US where the *American Institute of Architects* (AIA) identifies several levels of detail for models that correspond to different project phases [51]. Beyond being a BIM-based e-procurement platform, PLAGE is a project workflow and document management application and is thus used to manage models and processes right from the earliest stages, that is, the early program and concept design. The models were created using Archicad software and the design process was delivered in an integrated way, stimulating maximum collaboration between intervening actors.

Step 2. This step focused on the enrichment of the BIM model with information and Uniformat codes, which were manually included in each BIM component. For success, this process requires careful modeling (e.g., avoiding overlap


(a)

(b)

(c)

Figure 9: BIM models respecting different levels of detail (LOD100, LOD200, and LOD300, from (a) to (c)).

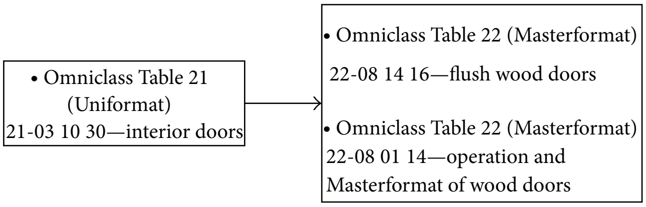


Figure 10: Example of link between element (interior doors) and work results.

between components of the model) to guarantee that the model is close to reality. The development and use of a BIM objects' library already including all the needed information is recommended.

Step 3. The IFC models were automatically generated from the BIM models originally created in the Archicad proprietary format. IFC interoperability concerns were given special consideration during this transformation. Particular attention was given to the problems that may arise due to the lack of interoperability between proprietary formats and IFC formats. As stated by Lipman et al. (2011), user expectations on IFC interoperability are not being met by CAD applications, which have been granted IFC certification and should be able to exchange 100% of the information in their CAD models via IFCs 100% of the time; however, they argue that the use of more adequate and systematized conformance and interoperability testing methodologies may lead to good results in terms of IFC interoperability. Meanwhile, in order to prevent major problems in IFC transformation operations, a careful analysis following IFC file generation should be conducted to assess possible errors. Special attention should be given to ground, materials, tailor-made objects (e.g., windows, doors, etc.), and specific elements subject to any advanced operation conducted by other BIM software (e.g., joints in complex walls or solid construction operations). Despite interoperability issues, IFC is crucial to collaborative work to facilitate a multisoftware approach to projects and to drive performance of construction supply chains to higher levels of interoperability [52, 53].

Step 4. This step begins with the login of the user to the PLAGE platform and the subsequent upload of the BIM model. This step may be repeated throughout the design process.

Step 5. According to the information models implemented in PLAGE platform, the EDM server stores and manages the IFC file and sends all relevant information to the Primavera CCOP software through web services. Subsequently, Primavera CCOP lists all of the construction elements using Uniformat based on the IFC tree view.

Step 6. This step focused the manual link between each BIM model component and the corresponding tasks (see example in Figure 10). This action was based on the Masterformat classification (Omniclass, Table 22) and was supported by external software, the Primavera CCOP, which enables organizing and classifying construction information. The Omniclass Construction Classification System (known as Omniclass or OCCS) includes 15 tables and integrates existing systems such as Masterformat (for work results), Uniformat (for elements), and EPIC—Electronic Product Information Cooperation (for products). According to the Construction Specifications Institute [54], Omniclass was designed to classify and organize information used by the construction industry throughout project lifecycles, encompassing all types of construction. By combining tables, one can develop BIM-based project execution guides with standardized information, reducing the mapping activities and common ad hoc nature of information management [55].

Step 7. Again, using the web services implemented, the Primavera CCOP software and the EDM server communicate, and the information produced in the previous step is included in the IFC model.

Step 8. At this point it is important to verify the conformance of the BIM model and inherent information. The user logs into PLAGE platform and, using the BIM viewer, checks the information related to each BIM component.

Step 9. In this step the BIM-based interface was used to launch RFQ or RFI. By selecting the elements of BIM model, it was possible to initiate the e-procurement/consulting process. In the present case only the RFQ of general BIM components were tested, that is, windows, doors, and another building equipment. The simulation was conducted with the involvement of the client and major contractor, who participated in the research project as partners.

Step 10. After the client/owner triggers the RFQ, web services exports the BIM technical and contractual data from the EDM server to the Vortal eGOV to launch the RFQ process. Besides the designs and specifications, the PLAGE Platform also releases the tender documents and the templates for the bid reply of the competitors. In this process complementary information may be added, such as expected dates for execution, maximum price, and selection criteria.

Step 11. In order to access the RFQ information, suppliers must log into the PLAGE platform, in which they view the BIM model and consult relevant information; the BIM-IFC file may be used by suppliers to analyze and make estimates in their own software through file transfer or web services (if previously set up).

Step 12. In this step suppliers used BIM viewer interface to add prices to BIM components, using a form or linking external files (such as pdf) to BIM components. The EDM server includes price information in the IFC file and creates pointers to external files that the supplier might submit.

Step 13. Finally, a multicriteria evaluation tool was used, implemented on the PLAGE platform in order to support the proposal's evaluation. It can be based exclusively on price or various criteria [17].

7. Discussion and Major Challenges

The proposed solution of BIM e-procurement was designed with the aim of providing a richer approach to the information flows associated with procurement, as it may foster more strategic approaches to e-procurement, by improving information management potential, stimulating collaboration, and maximizing supply chain management. In traditional e-procurement platforms, collaboration arises primarily from buying requirements for procurement through the specification development process, using real-time communication and exchange of information [56, 57]. However, a BIM-based e-procurement vision may extend these capabilities to design and develop products, manufacturing processes, logistics, and distribution strategies.

The chosen case study research design consisted in a qualitative research, which allowed a description of the interaction of context and actors in a specific setting [58]. While the quantitative research is concerned with identifying relationships between variables and generalizing those results to the world at large, the qualitative research seeks to understand phenomena in depth and within specific contexts [59]. Considering this, the present research has conducted several interviews with the members of the testing team, which allowed identifying the major gains of the proposed solution.

From this specific case study, and based on the expertise of the interviewed professionals, it is possible to sustain that BIM-based e-procurement may reduce the time and effort variables related with information management activities that have heavy contractual and administrative procedures and documentation, as BIM model will serve as a unique repository to all this information, both to the owner, contractors, designers, or subcontractors. Moreover, it is expected that as the various agents involved in the procurement process may reuse BIM elements, buyers and suppliers will enhance the integrity and reliability of information used, diminishing the errors due to information operation. These benefits were clearly identified by the interviewees in qualitative research but it was not the focus of the research to measure or quantify these benefits.

However, these benefits are shadowed by the costs associated with the required additional effort to edit the documents and linkages to the BIM model and maintain a procurement process using coherent information between product model, quantities, product descriptions, and contractual arrangements centered on a BIM model. This editing requires currently specialized technical support to combine the various information sets into the BIM-based procurement process. Although the traditional process also requires editing a substantial part of the information for the procurement process, the effort does not require a unified treatment of documents and there is a more fragmented approached to information and documents management. Indeed, the approach requires a deep understanding about how to create the models and how to classify the information included in the models using predefined taxonomies and linkage of vectorial and nonvectorial information within a BIM Viewer.

Although the research project did not accurately measure the additional effort for the procurement process in comparison with traditional procurement mechanisms, the various partners involved in the process recognized that the learning curve was considerable and that it did not make the new administrative process overall more streamlined.

Although the BIM-based e-procurement interface has shown itself to be useful, the success of its implementation requires a deep understanding about how to create the models and how to classify the information included in the models using predefined taxonomies. This issue is very important as in construction projects procurement of trade services and products tends to be a one-time activity, and thus there are few opportunities for gaining efficiency due to replication of the process. Moreover, there were several difficulties that emerged with the pilot case study that were not anticipated.

A fundamental hindrance was the ability to convert individual building objects in aggregate product and service "blocks" that are released to tender. The major problem is on the level of aggregation, because BIM objects tend to be very elementary and tenders focus on aggregate levels of products and services. Quantities for tendering are easy to obtain directly from the BIM model, but how to organize the elements to be tendered is a rather complex issue, and the existing models do not reflect this need. It is easy when the blocks are windows, doors, or other highly specific products but it becomes considerably harder when there is a need to aggregate with works that involve other types of products or trade services.

Some problems were identified regarding the interoperability models: when transformed into IFC the models lost some information included in the original proprietary format. It was also found that there are no specific IFC classes for procurement related information, which can hinder interoperability in procurement processes. Furthermore, it was evident that the wide implementation of the solutions proposed depends to a great extent on the dissemination of standardized taxonomies. Using predefined information classifications for BIM elements, work results, products, resources, and so forth cannot be avoided because these classifications must be common to the various actors to guarantee that the same codification will be used for a specific piece of information. This is particularly important whenever information flows across organizational boundaries, from procurer (buyer) to tenderer (supplier) that may have different modeling configurations and working practices that should be previously aligned.

Although the research project has uncovered several hurdles, the BIM-based e-procurement prototype presented in this paper demonstrated successful results. The parties involved, including the owner of the building and one of the major national general contractors, considered the solution opportune and useful and reported the importance of stimulating increasingly integrated and collaborative processes using innovative ICT. Several benefits have been identified as quite promising in terms of replicating the pilot in other full-scale construction projects. First, the need for the procurement process to input information in the BIM model has proven to be very useful as the model becomes a natural repository for all technical, managerial, administrative, and contractual information about the project. Indeed, rather than having several digital repositories of the project, agents in the project have a user-friendly interface—the BIM Viewer—for the most important documents facilitating the search, retrieval, distribution, and storage of documents and information, because they are connected to the model. This is particularly useful for all contractual procurement administrative documentation, as in construction projects these are a large part of all information. Hence, though the approach adds to the size and complexity of the BIM model, it significantly improves information management.

Second, as the buyer triggers the procurement workflow the IFC exportation of the technical and contractual data from the BIM model to the platform occurs. In addition to the architectural designs and specifications, the platform also releases the tender documents and the templates for the bid reply of the suppliers. In this process complementary information may be added, such as expected dates for execution, maximum price, selection criteria, and so forth. However, this information is incorporated in the tender documents through a structured procedure that also feeds the original BIM model. Hence, a fair amount of reusability is possible, in both directions, of the information, models, and data between agents. Of particular value is the fact that buyers and suppliers can avoid the reentry of data and re-creation of models, with all the errors and misfits that typically occur in these replication processes.

Although there was a major effort to have mainly structured information in the e-procurement process, the platform also supports some complementary unstructured information in the tender document sent by the suppliers. As a result, the BIM-IFC detailed design and the filled-in bid template may contain additional information in the form of attached files (e.g., pdf format, jpg, etc.) or possibly Web links. However, each element of unstructured information has to be linked to an object within the BIM model. This complementary information and documentation may also be incorporated directly in the BIM Model (rather than being imported along with the original file), through the manipulation of the BIM Model Viewer, thereby enriching the content of the model.

The research includes some limitations related to its complex approach (i.e., action research involving several actors, distinct perspectives, and multiple phases). Such research is demanding in terms of planning and management. In some instances the research is unable to offer complete answers to the questions raised, so the approach focused primarily on the problem setting than problem solving. Nevertheless, it achieves results reflected in various viewpoints that enrich the state of the art and leverages the pertinence of final findings.

Appendix

The information model implemented in the EDM server in order to allow an efficient management of the project data is briefly described in the following, giving special attention to the entities implemented on the EDM server.

(i) Project. This entity represents a specific project, which has several phases. The "currentPhase" attribute is the phase in progress and all the historic information is stored on the "previousPhase." Each project has a unique identifier ("instanceID") in the server, which must be used by the client

application to access project information. Each project has a dedicated workspace in the model server, where the models and other project information ("owner," "description," "dateCreated," "startDate," and "endDate") are stored.

(ii) ProjectPhase. This entity represents a project phase and allows managing all the information related to that specific phase. Each phase may include a main model ("mainModel") and other models ("models"), which may include distinct information. During a specific project phase several requests for information or quotation can be made ("RequestForQuotations"), which can then be classified into distinct stages: "OpenForQuotation," "QuotationEvaluation," "Execution," and "Closed".

(iii) ProjectModel. This entity represents a model in a project, which is necessarily related to a specific project phase. Several attributes were defined to characterize the model such as the model version ("version"), the model type ("modelType"), a brief description of the model ("description"), the owner of the model ("responsible"), and the creation date ("dateCreated"). An attribute to identify the status of the model (editable or blocked) was also implemented ("frozen").

(iv) RequestForQuotation (RFQ). This entity allows managing the requests for information or quotation, which are always related to a specific phase. It collects the several quotations ("quotations") and allows identifying the winning tenders ("awarded"), if applicable. Besides the information/quotations, this entity allows for attaching a model to the RFQ ("baseModel"), which becomes the support for the generation of tenders. Additionally, this entity collects generic information about the RFQ, such as the start date ("startDate"), the expected ending date ("endData"), and the RFQ status ("RFQStatus"), which can be "Open" or "Closed."

(v) Quotation. This entity represents a tender/information and is related to a specific RFQ. It includes information about the RFQ process ("associatedRFQ"), the tenderer ("responsible"), submission date ("dateSubmited"), comments about tender evaluation (if applicable) ("notesOnEvaluation"), the status of the quotation ("valid"), and the IFC models related to the quotation ("models").

On the other hand, the information model which defines the information flow based on the IFC objects included in the IFC model has three entities.

(vi) TaskView. This entity represents a task on the PLAGE platform, which corresponds to the ifcTask entity in the IFC standard [60]. Each task may contain several subtasks. This entity includes several attributes, such as the following:

(i) instanceId: identifies the task according to the ifcTask entity;

(ii) globalId: Universally Unique Identifier (UUID), included in the correspondent ifcTask entity in the IFC file;

(iii) name: name of the task;

(iv) numberOfElements: states the number of IFC elements related to the task;

(v) state: refers to the status of the task, useful to monitor any change made to the task entity;

(vi) propertiesChanged: indicates if any property of the task has been changed;

(vii) plageProperties: describes the set of properties defined by the Plage platform, which are related to the correspondent "ifcTask";

(viii) otherProperties: any other property related to a specific "ifcTask";

(ix) elementsChanged: indicates if any element related to the task has been changed;

(x) elements: defines the set of elements related to the task;

(xi) tasksChanged: indicates if the task has been changed;

(xii) numberOfChilds: states the number of subtasks of the task;

(xiii) childTasks: defines the subtasks of the task;

(xiv) isLastVersion: states if the entity is the last version of the task.

(vii) ElementView. This entity represents an IFC object and all the elements related to the IFC standard entity "ifcElement" [61]. This entity includes several attributes, such as the following:

(i) instanceId: identifies an element according to the ifcElement entity;

(ii) globalId: Universally Unique Identifier (UUID), included on the correspondent "ifcElement" entity on the IFC file;

(iii) name: name of the element;

(iv) description: description of the IFC element;

(v) propertiesChanged: indicates if the properties of the element have been changed;

(vi) plageProperties: describes the set of properties defined by the Plage platform, which are related to the correspondent "ifcElement";

(vii) otherProperties: any other property related to the correspondent "ifcElement";

(viii) elementType: refers the type of IFC element;

(ix) state: indicates the status of the element allowing for the monitor ing of any change in task structure; concretely it tells if the element has been included or removed from a specific task;

(x) isLastVersion: states if the entity is the last version of the element;

(xi) parentSpatialStructureName: indicates the name of the spatial structure in which the IFC element is inserted;

(xii) parentSpatialStructureID: shows the identifier of the spatial structure in which the IFC element is inserted;

(xiii) parentSpatialStructureType: type of the spatial structure in which the IFC element is inserted.

(viii) PropertyView. This entity represents a property related to the IFC element and corresponds to the IFC entity "ifcProperty." This entity includes several attributes, such as the following:

(i) instanceId: identifies the property according to the ifcProperty entity;

(ii) name: name of the property;

(iii) description: description of the IFC property;

(iv) units: SI unit of the property;

(v) propertyType: type of property;

(vi) propertySetName: name of the property set to which the property belongs;

(vii) changed: indicates if the property has been changed;

(viii) propertyValue: defines the value corresponding to the property [62].

Several web services have been also implemented in the EDM server to satisfy the management requirements of the PLAGE platform, such as the following:

(i) access control services: login and logout;

(ii) project management services: CreateProject, addModelToCurrentProjectPhase, getProjectById, and getProjectByWorkspace;

(iii) model management services: uploadProjectModel, DownloadProjectModel, getTasksAndQuantities, getTaskElements, updateTasksAndQuantities, getAllRootTasks, getAllModelElements, and getModelElementsOfType.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

Assigning Robust Default Values in Building Performance Simulation Software for Improved Decision-Making in the Initial Stages of Building Design

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Applying data mining techniques on a database of BIM models could provide valuable insights in key design patterns implicitly present in these BIM models. The architectural designer would then be able to use previous data from existing building projects as default values in building performance simulation software for the early phases of building design. The author has proposed the method to minimize the magnitude of the variation in these default values in subsequent design stages. This approach maintains the accuracy of the simulation results in the initial stages of building design. In this study, a more convincing argument is presented to demonstrate the significance of the new method. The variation in the ideal default values for different building design conditions is assessed first. Next, the influence of each condition on these variations is investigated. The space depth is found to have a large impact on the ideal default value of the window to wall ratio. In addition, the presence or absence of lighting control and natural ventilation has a significant influence on the ideal default value. These effects can be used to identify the types of building conditions that should be considered to determine the ideal default values.

1. Introduction

Just as the implementation of high-efficiency HVAC and lighting systems and the use of natural energy are necessary in green building design, a well-designed architectural plan is important to minimize energy use in the building. Computer simulation tools, such as energy simulation tools, can be very useful in the development of such an optimal architectural plan [1]. For example, energy simulation tools can be useful in producing an enhanced sketch of the building shape that best minimizes energy consumption in early stages of the building process [2].

The implementation of energy simulation tools at the early stages of building design has high value in view of energy saving. However, energy simulation tools require several inputs. It makes energy simulation a time-consuming task [2]. In addition, the numerous uncertainties in these inputs make it difficult to perform an energy simulation efficiently in the real design process, especially when determining the building shape in the early stages of building design [3]. Information based on simulations with poor choices for the inputs may provide inaccurate information for decision making. It may also cause poor building performance.

How to handle the uncertainties is also an important topic in building information modeling (BIM [4]) technology development [5]. Based on this philosophy, the author has been developing an optimal building design aid system that integrates computer aided design (CAD), building environmental simulation tools and an optimization algorithm, based on the concept of BIM [6]. As an answer to these discussions, a new method assigning default values based on the past project records in building performance simulation software has been proposed [7]. The default values are defined as tentative values that are required in simulations in the initial stages of building design. The usage reduces the errors in building environment assessments by increasing the robustness of the building performance simulation results. In this paper, a more convincing argument is presented to utilize the new method to assign appropriate default values to a new building project.

2. Definition and Importance of Default Values at Early Stages of Building Design

The building shape has a large impact on the energy consumption of the HVAC and lighting systems. Thus the building shape is assigned first priority in the design [8–10]. In this context, the optimal building shape in view of energy saving should be developed as early as possible in the initial design stage [11, 12]. The façade, including the window proportions and the window areas, might be dictated by the architectural style and the sketch ideas could be guessed at the same time when the building shape is studied. However, the suitability for the building performance is not validated at this stage. Thus, these parameters should be optimized at the next design stage [13]. In addition, façade composition including glazing type and thickness for external walls might be dedicated based on green building guidelines. However, the optimal figures for these parameters vary according to building layout including the orientation [14]. Thus, these parameters might be changed due to detailed thermal energy and economic analysis at the later design stages. In these contexts, the sketch of the building shape should be studied in conjunction with the uncertainties in the façade features.

To carry out an energy simulation at this early design stage, tentative values must be carefully chosen for the numerous inputs that have not yet been determined. Some studies have identified the lack of quality in the model data related to the uncertainty as one of the main issues preventing the effective adoption of BPS in industry. Despite the development of BIM technology, which can aid in the input of building geometry, tentative values are still necessary for building properties and all nongeometric data inputs, such as the window properties [15]. In this study, these tentative values with uncertainty are called "default values" [7]. The use of "default values" is an advantage in many simulation tools; however, input quality control is one of the missing features regarding usability [16]. For example, the building proportion is a design variable when the building shape sketch is being developed. Meanwhile, the other values such as the window properties and the wall compositions that are studied at a later stage must be treated as "default values." However, the design variables should include not only the building shape but also those default values that affect the optimization outputs. That is, the optimal design value is highly affected by the default values. A poor choice of default values, therefore, can direct an architect toward ineffective building shapes, which can result in buildings with high energy consumption. In other words, a realistic design approach is to introduce ranges of uncertainty in the simulation parameters including the default values [17]. In particular, the window properties, such as the glazing percentage and the orientation, strongly influence the output [18]. Moreover, the building operation, for example, the implementation of natural ventilation, affects the optimal window properties [19]. Thus, thoughtful consideration is required in assigning default values to the window properties. The optimized design solutions must be robust enough to changes in the design conditions and to identify solutions that are less susceptible to uncertainty [20]. Thus, the demand of research for investigating the sensitivity of design condition is increasing [21].

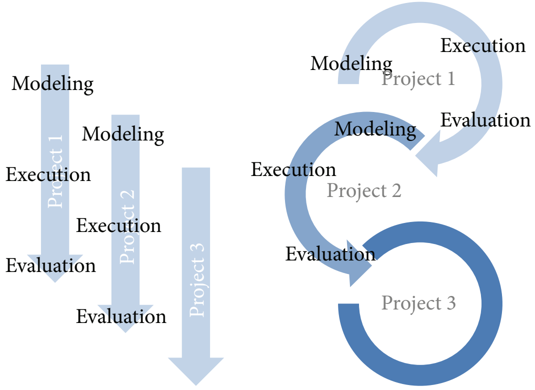
To ensure the robustness of the optimized design solution, background data, such as the energy simulation results, should also be sufficiently robust to the uncertainties in the inputs, which may vary in subsequent design stages. Thus, the ideal default value should be defined to ensure robustness. The default values should comprise the values that maximize the robustness instead of the optimal values that minimize the object functions, such as energy consumption. Note that the default values are expected to be treated as design variables and will be optimized in a subsequent design stage.

It is difficult to find a global default value that can be applied to any type of building design. The optimal building design is strongly dependent on the climate [21]. Thus, building components that can be adapted to different climates should be employed.

The question then arises as to whether default values based on different climates can be developed, just as each country has its own green building guidelines. It may be possible to define appropriate default values for simple properties such as the glazing type. However, window properties such as the window geometry are strongly dependent on the building shape and the building operation [18]. That is, the original window properties of each building should maximize the energy efficiency based on the building shape and operation. Therefore, there are as many appropriate default values as there are varieties of buildings [7].

To assign appropriate default values to a new building project, an experienced architect searches for the best practice that shows similarities to the new project to minimize ranges of uncertainty. In a survey of current building simulation workflows in professional practice, 31% of the participants indicated that they reused a previous model for building information inputs [15]. An architect usually aims to determine the best practice that is suitable for a new project. BIM can help to reduce the effort expended by architects in searching for best practices.

In BIM technology development, data-mining techniques are controversial [22]. However, there appears to be less debate on how to search for data from existing building data sets. The building information is represented as the assembly of objects in BIM that employs the object-oriented databases. Existing building objects are highly developed adaptations to previous building projects that account for the unique features of the building. These concepts can be used in knowledge transfer methods by employing the features of existing building parts to benefit a new building design that has similarities to the previous project [23]. In a previous paper, a method was presented for using building attributes for a new project that had been optimized using previous building designs [7, 24]. Figure 1 shows the



(a) Conventional method (b) New method using proposed default value

Figure 1: Image of simulation flow.

image of the simulation process using a conventional method (Figure 1(a)), in contrast to the simulation process displayed in Figure 1(b), in which the default values are used that were proposed from previous studies.

Although all building properties are individually inputted using a conventional method (Figure 1(a)), the simulation inputs are transferred from the previous studies using proposed default values in the proposed simulation flow (Figure 1(b)).

In this paper, a more convincing argument is presented to show the significance of the new method. Case studies are performed to optimize window properties under various conditions for the building shape, climate, and building operation modes, such as lighting control and natural ventilation. First, the variation in the optimal window properties under different conditions is investigated. Then, the relationship between the optimal properties and each of the conditions is determined. These relationships are used to develop a strategy for searching for similarities between a new project and previous projects to determine appropriate "default values" for the new project.

This study focuses on window-to-wall ratio (WWR) for two reasons. The first reason is the significance of the impact on the simulation results. The sketches of the building shape and location are discussed at the beginning of building design. Building performance simulations are extremely important because the two factors are critical to the building performance. The default value of WWR is required. Another reason is the feasibility of the proposed method. The window data are easily output from the BIM data, such as the industry foundation classes (IFC) data model [25].

3. Case Study

3.1. Calculation Scheme. First, various optimal solutions under different conditions are determined. We consider a window design problem that is often used in case studies for optimization research [26]. A three-story office building model is used in this case study. Several properties of this building model can be set parametrically, so that the influence of default values can be properly investigated. One of these properties is the floor area of one floor, which can be set to 400 or 1600 m^2. In this study, only the second floor is considered to determine the building output. The floor height is 3.5 m, including the plenum space.

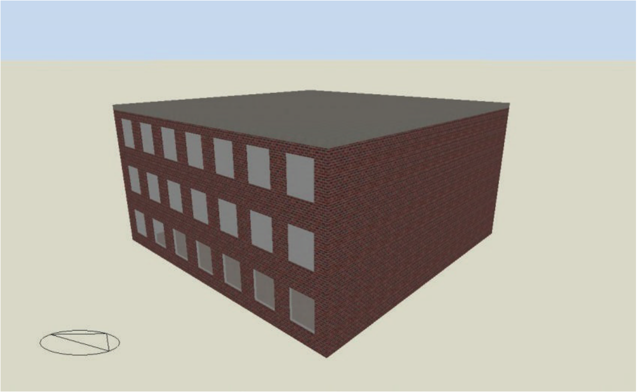


Figure 2: Building object.

Figure 2 shows the building object with a floor plan of 400 m^2. The building object with an area of 400 m^2 is regarded as a small-scale building with a small space depth from the window, whereas the building object with an area of 1600 m^2 is regarded as a large-scale building with a large space depth. The design variable for the optimization is the window-to-wall ratio (WWR), which strongly affects the energy use of a building. The glazing is generated for a window height of 2.0 m, but the window height can be adjusted to achieve the required WWR. The objective function is the annual CO_2 emission.

Case studies are conducted based on energy simulations for various conditions, building sizes, orientations, building operation modes, such as lighting control and natural ventilation, and weather data. The weather data for ASHRAE/TMY3 in Boston, MA, USA, are chosen to represent a subarctic climate, and the weather data for ASHRAE/TMY3 in Miami, USA, are chosen to represent a subtropical climate.

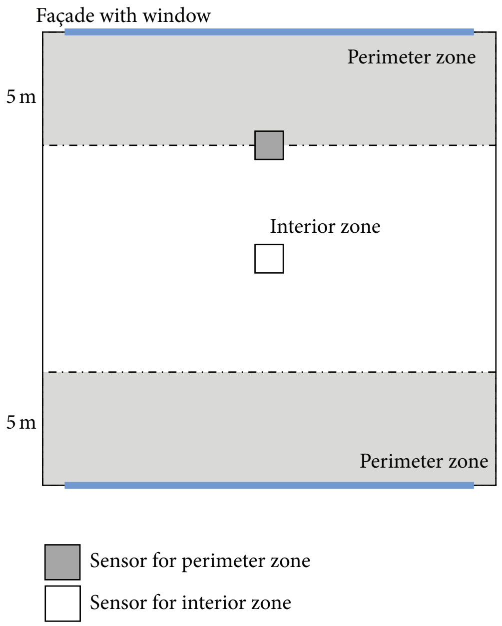


FIGURE 3: Sensor locations.

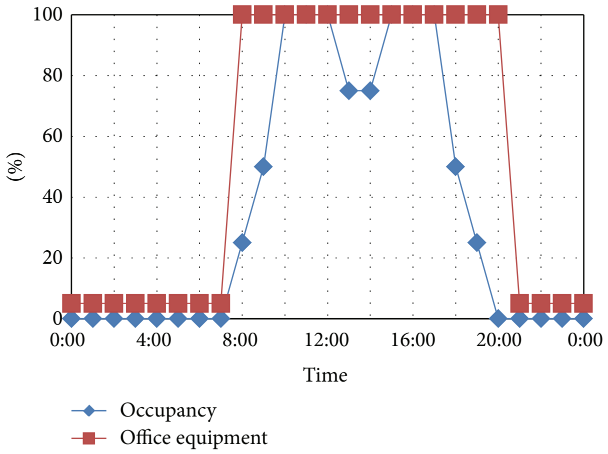


FIGURE 4: Schedule for internal heat load.

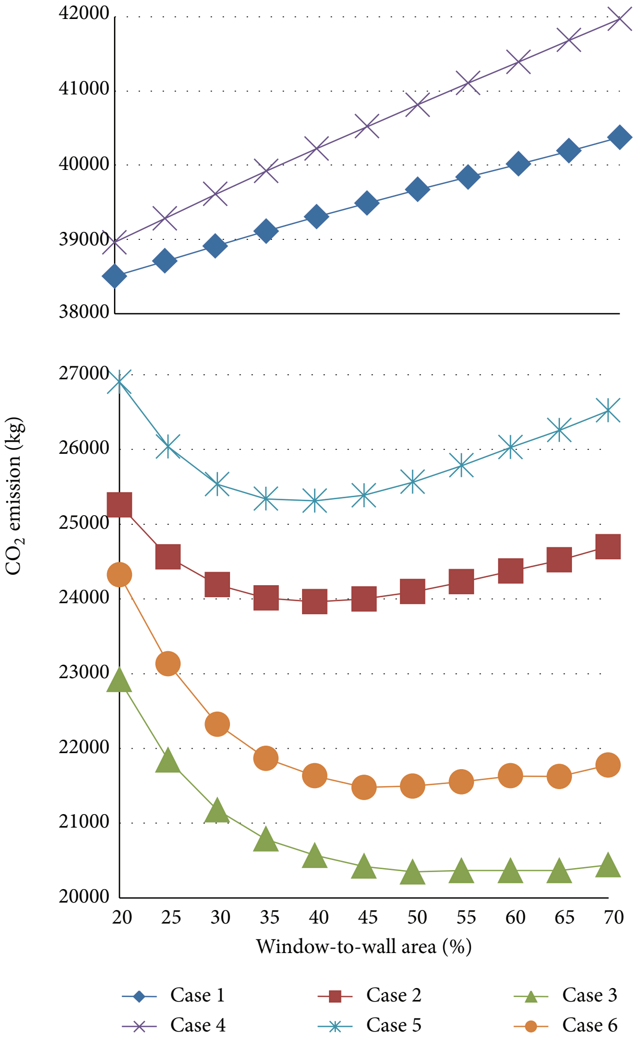


FIGURE 5: Results for cases 1–6.

Lighting control depending on daylight use is simulated for the building operation. The office area is separated into two zones: a perimeter zone and an interior zone. The perimeter zone is the area that falls within a 5.0 m distance from a wall with windows. Each zone contains an illuminance sensor. This sensor is located at the center of the office in the interior zone. In the perimeter zone, the sensor is located at the boundary between the two zones. The sensor locations are shown in Figure 3.

Natural ventilation that depends on the external air temperature is simulated. The windows open when the interior air temperature is higher than both the external air temperature and the set point temperature. The set point temperature is 24°C. The window openings are modulated by the temperature difference between the interior and the exterior. The maximum opening area is 20% of the window area. This opening area is multiplied by a factor from 0 to 1. When the temperature difference between the interior and the exterior is less than 4°C, this factor is 1. The factor decreases linearly as the temperature difference increases and becomes 0 for a temperature difference of 8°C. The ventilation is cross ventilation. The ventilation rate through each opening is calculated based on the pressure difference using wind pressure effect.

The variable conditions for the case studies are shown in Table 1. The remaining conditions are the same for each case, as shown in Table 2. The activity schedules are shown in Figure 4. Design Builder [27] integrating Energy Plus [28] simulation engine were used for the simulations. Only the energy consumption of the second floor is considered in these case studies.

3.2. *Calculation Results (Boston).*

Figure 5 shows the calculation results for cases 1–6, using the weather data from Boston for a floor area of 400 m^2. In cases 1 and 4, neither the lighting control nor the natural ventilation control are simulated.

Table 1: Variable conditions for the case studies.

Case	Operation	Window orientation	Area of each floor [m^2]	Weather data
1	None	North and South	400	Boston
2	Lighting control			
3	Lighting control, natural ventilation			
4	None	East and West		
5	Lighting control			
6	Lighting control, natural ventilation			
7	None	North and South	1600	
8	Lighting control			
9	Lighting control, natural ventilation			
10	None	East and West		
11	Lighting control			
12	Lighting control, natural ventilation			
13	None	North and South	400	Miami
14	Lighting control			
15	Lighting control, natural ventilation			
16	None	East and West		
17	Lighting control			
18	Lighting control, natural ventilation			
19	None	North and South	1600	
20	Lighting control			
21	Lighting control, natural ventilation			
22	None	East and West		
23	Lighting control			
24	Lighting control, natural ventilation			

Table 2: Simulation conditions.

U value	Outer wall: 0.25 W/m^2K (concrete block and brickwork) Ground floor: 0.15 W/m^2K, roof: 0.15 W/m^2K Window: 1.96 W/m^2K (double glazing)
Window	Double glazing, *U* value: 1.96 W/m^2K, total solar transmission (SHGC): 0.70, direct solar transmission: 0.62, and light transmission: 0.74
Window shading	Blind with high reflectivity slats Solar setpoint for cases 1, 5, 9, 13: 120 W/m^2 Maximum allowable glare index for the other cases: 22.0
Internal heat	Human: 0.1 person/m^2, 123 W/person, office equipment: 11.8 W/m^2
Lighting	3.3 W/m^2—100 lux Target illuminance: 400 lx
Mechanical ventilation	10 L/s-person
Heating	Natural gas (carbon emission factor: 0.195 kg CO_2/kWh) Heating system CoP: 0.830 Schedule: 5:00–19:00 in weekday: on, all other periods: on by set-back temp. Setpoint temperature: 22°C, set-back temperature: 12°C
Cooling	Electricity from grid (carbon emission factor: 0.685 kg CO_2/kWh) Cooling system CoP: 1.670 Schedule: 5:00–19:00 in weekday: on, all other periods: off Setpoint temperature: 26°C

In these two cases, the larger the WWR, the higher the CO_2 emissions. The cooling load increases with the window area due to the increase in solar gain and heat transmittance through the window.

In cases 2 and 5, daylight-dependent lighting controls are simulated. In these two cases, the CO_2 emissions are clearly reduced by using lighting control in comparison to cases 1 and 4, in which lighting control is not used. Increasing

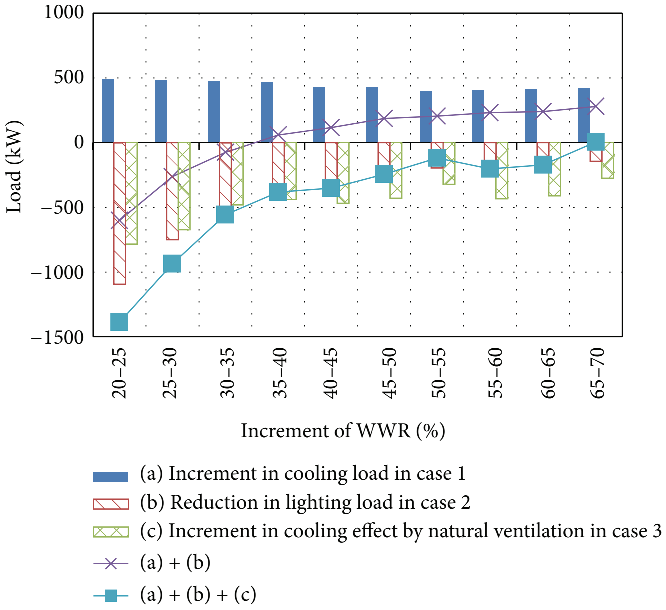


Figure 6: Influence of window area.

the window area increases the potential for daylight use. In both cases, this effect is clearly shown for a WWR of approximately 40%. However, this daylight effect saturates when the WWR exceeds 50%. Moreover, the CO_2 emissions increase with the window area. The results seem to be comparable to other evaluation results in references [29] and the ANSI/ASHRAE/IESNA1 Standard 90.1-2010, which attained a maximum WWR of 40%. Thus, increasing the window area beyond 50% of the wall area is not effective for reducing CO_2 emissions.

In cases 3 and 6, natural ventilation and lighting control are simulated. In these two cases, the effect of cooling by natural ventilation and lighting control can be clearly observed when the WWR reaches 50%. Beyond this value, the window areas have a small influence on CO_2 emissions. Although the CO_2 emission rates for cases 4–6, in which the windows face east and west, tend to be larger than those for cases 1–3, in which the window orientations are north and south, similar trends of increasing CO_2 emissions are obtained for larger window areas.

Figure 6 shows the influence of the window area on the cooling load for case 1, the lighting load reduction achieved with lighting control for case 2, and the cooling effect of natural ventilation in case 3 (see (a), (b), and (c) in Figure 6, resp.). The cooling load in case 1 increases monotonically with the window area. However, the lighting load reduction in case 2 decreases as the window area increases. For the cases in which only lighting control is activated, cases 2 and 5, the lighting load reduction achieved by lighting control is larger than the increase in the cooling load obtained by increasing the window area up to a certain WWR. An inflection point is then reached at which the lighting load reduction becomes equal to the HVAC load increment (see (a) + (b) in Figure 6). The inflection point occurs at a WWR of 40% in this case study. Thus, a single optimal WWR can be determined. The optimal WWR is approximately 40% in cases 2 and 5. As shown in Figure 6, the cooling effect of natural ventilation increases almost monotonically with the window area. For the cases in which both lighting control and natural ventilation are simulated, cases 3 and 6, the CO_2 emission decreases until the glazing percentage reaches approximately 50%, as found for cases 2 and 5. The influence of the glazing percentage on the CO_2 emissions becomes very low because lighting control has a very small effect, whereas the constantly increasing cooling effect of natural ventilation is nearly equal to the increase in the cooling load obtained by increasing the window area (see (a) + (b) + (c) in Figure 6).

Figure 7 shows the results for cases 7–12, which have floor areas of 1200 m^2, and the space depth is large. In cases 7 and 10, neither lighting control nor natural ventilation control are simulated. In these two cases, the larger the WWR, the higher the CO_2 emission, as was found for cases 1 and 4. However, as the window area increases, the CO_2 emission monotonically decreases for all of the other cases. Thus, daylight use achieved by increasing the window area is always expected to reduce CO_2 emissions, even though the influence gradually decreases. Thus, the design with the highest WWR is the best solution for cases with a relatively large floor area and large space depth.

3.3. Calculation Results (Miami). Figure 8 shows the results for cases 13–18, based on the weather data from Miami for a floor area of 400 m^2. Compared to Figure 5, the same trends are observed for the influence of the window area on the CO_2 emissions. However, the inflection points of the CO_2 emission curve are more obvious than those observed in Figure 5. Although it is difficult to find an optimal WWR in cases 3 and 6, a window area of 40% can be used as the optimal percentage in cases 15 and 18.

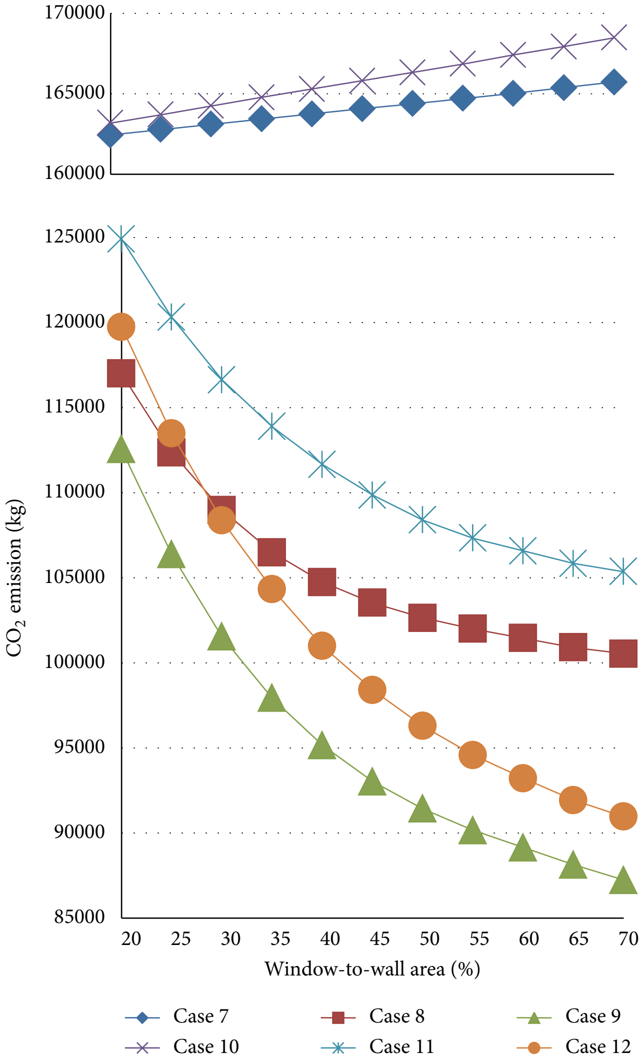


FIGURE 7: Results for cases 7–12.

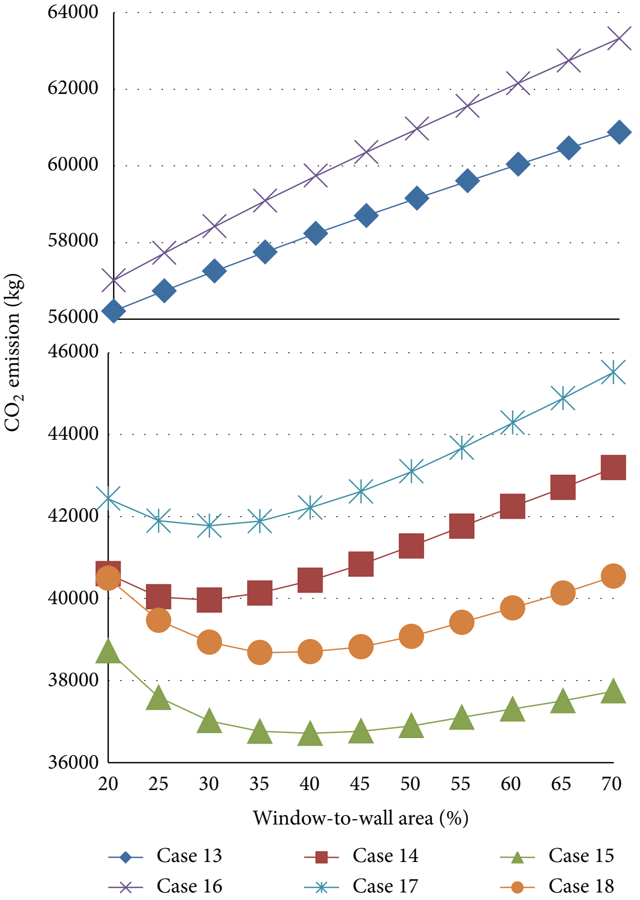


FIGURE 8: Results for cases 13–18.

Figure 9 shows the influence of the window area on the cooling load for case 13, the lighting load reduction for case 14, and the cooling effect due to natural ventilation in case 15 (see (a), (b), and (c) in Figure 9, resp.). The trends shown in Figures 9 and 6 differ in that the increase in the cooling load is relatively larger than those for the lighting load reduction and the cooling effect by natural ventilation. Thus, when the WWR reaches an inflection point, the lighting load reduction becomes equal to the HVAC load increment (see (a) + (b) in Figure 9). Even for natural ventilation operation, the increment in the cooling load becomes larger than the sum of the lighting load reduction and the cooling effect as the window area increases. Thus, an inflection point can be observed even for the case with natural ventilation (see case 15 in Figure 8 and (a) + (b) + (c) in Figure 9).

Figure 10 shows the results for cases 19–24, which have floor areas of 1200 m^2. In comparison to Figure 5, the same trends are observed for the influence of the window area on the CO$_2$ emissions. Thus, the weather data do not exert a significant effect on the optimal window area for cases with a relatively large floor area and a large space depth from window. A reduction in CO$_2$ emissions is expected because the increased window area contributes to a lighting load reduction and the possibility of using natural ventilation in all of the cases considered.

4. Discussion

The ideal "default values" referenced in the "Introduction" are discussed in this section. When a building shape sketch is discussed at the early stage of building design, an energy simulation must be implemented to estimate the energy performance of the building. In energy simulations, the window properties, especially the WWR, exert a strong effect on the output. Thus, accurate inputs are needed to obtain an optimal building shape that maximizes the energy performance of the building. However, the window properties are generally not considered at this stage because the building shape sketch is usually considered at the first stage of the building design. Thus, tentative values should be assigned to the window properties to implement the energy simulation. However, these tentative values will be changed at a later stage of building design, when the window properties are treated as design variables. Thus, one must choose a tentative value that minimizes the variation in the calculation results when the value is changed at a later stage in the building design.

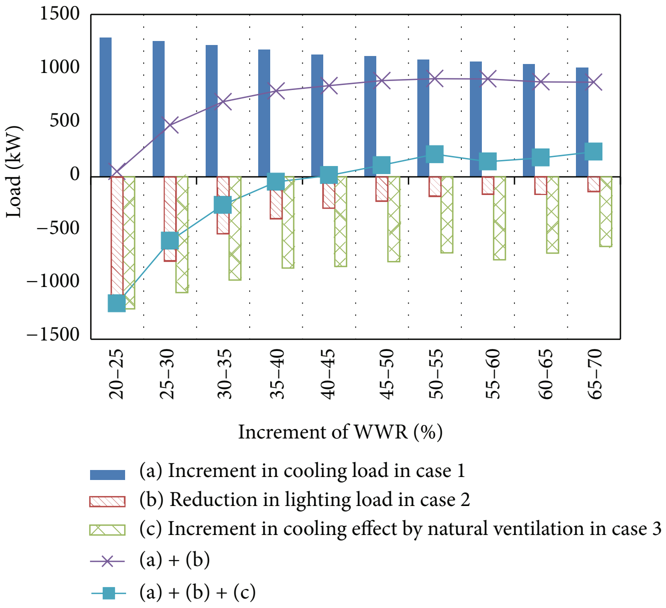


Figure 9: Influence of window area.

4.1. Evaluation of Default Value Using Average Value of Error. We illustrate this concept using the case study presented in Section 3. Figure 11 shows the average value of the error when different WWRs are used as tentative values. The average values of the error are calculated using the following equation:

$$E(i) = \sum_{j} \frac{Q_{i,j} - Q_{\min,j}}{Q_{\min,j}} \times \frac{100}{n}, \qquad (1)$$

$E(i)$ is average value of the error [%], $Q_{i,j}$ is CO_2 emission for case j when the tentative WWR is i% [kg], $Q_{\min,j}$ is minimum CO_2 emission for case j [kg], and n is total number of cases used to calculate the average value.

The error $Q_{i,j} - Q_{\min,j}$ is the amount of change that results from the change in the default value at a subsequent stage in the building design. The amount of change is divided by the minimum CO_2 emission $Q_{\min,j}$ as the calculation results using the optimal WWR to express the value as a percentage. The percentage is assumed to be the error range in the simulation results in the initial stages of building design. Minimizing the value of this change maintains the accuracy of the simulation results in the initial stages of building design. In this equation, each value is assumed to have an equal probability of being selected as the default value and the default value is assumed to be optimized to reduce the CO_2 emission at a subsequent stage in the building design.

The Boston data are used in the calculations for cases 1–12, and the Miami data are used in the calculations for cases 13–24. For the cases in which the Boston data are used, the average value of the error is minimized for a WWR of approximately 65%. Thus, a relatively large window area can be used as the ideal default value in a subarctic climate area such as Boston. However, for the Miami cases, the average value of the error is minimized for a certain WWR, such as 40%. Thus, expanding the window area is not necessarily a good strategy for reducing CO_2 emissions by daylight use and natural ventilation. A modest WWR should be used as the ideal default value for a subtropical climate area such as Miami.

4.2. Grouping of Cases to Increase Adequacy in Default Value. Figure 12 shows the WWRs that produce the minimum average value of the error, grouped by cases with a common building feature. Figure 12(a) shows the results for the cases with a floor area of 400 m^2, cases 1–6 and cases 13–18. An optimum WWR of 30% should be used as the default value for this condition. Figure 12(b) shows the results for cases with a floor area of 1600 m^2, cases 7–14 and cases 19–24. In this scenario, an optimum WWR of 70% should be used as the default value, corresponding to twice the value found for a floor area of 400 m^2. This result implies that the default values should be selected based on the space depth related to the floor area. If the building scale is large and the space depth is large, as in case (b), a relatively large ideal default value should be used. The effects of daylight use and natural ventilation can be expected for larger window areas. However, if the building scale is small and the space depth is small, as in case (a), a modest WWR should be used as the ideal default value.

Figures 12(c) and 12(d) show the results for cases in which the window orientations are north/south and east/west, respectively. In both cases, modest WWRs, near 50%, result in the minimum average value of error. Thus, the window orientation has little effect on the optimal default value.

Figures 12(e), 12(f), and 12(g) show the results for cases with different operation modes of lighting control and natural ventilation. If neither operation is employed, as in case (e), the window area should be minimized because increasing the window area directly increases the HVAC load. However, when lighting control is used, increasing the window area is

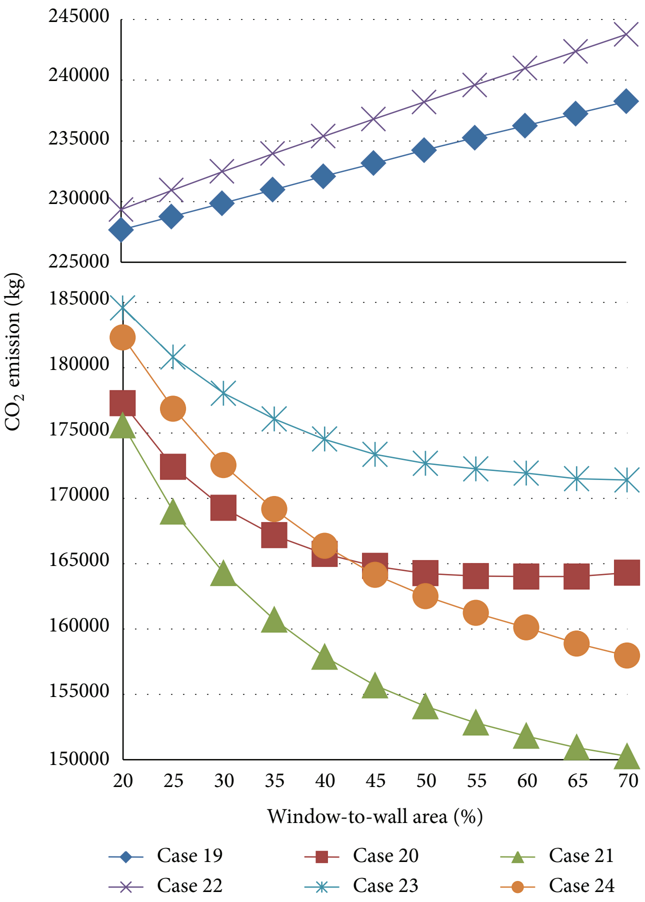


FIGURE 10: Results for cases 19–24.

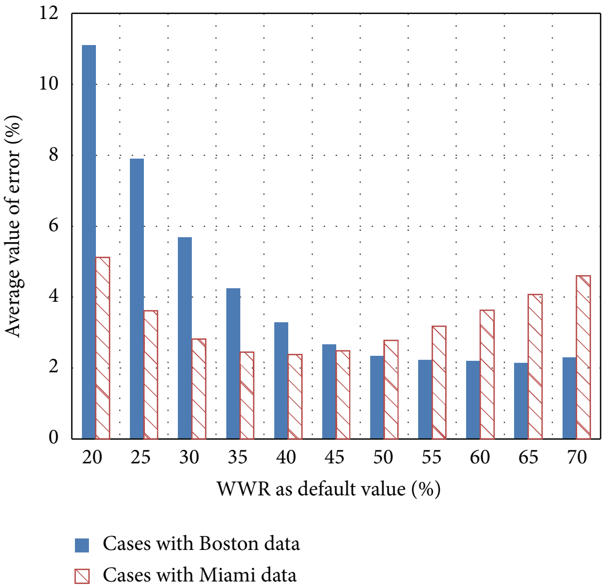


FIGURE 11: Average value of the error.

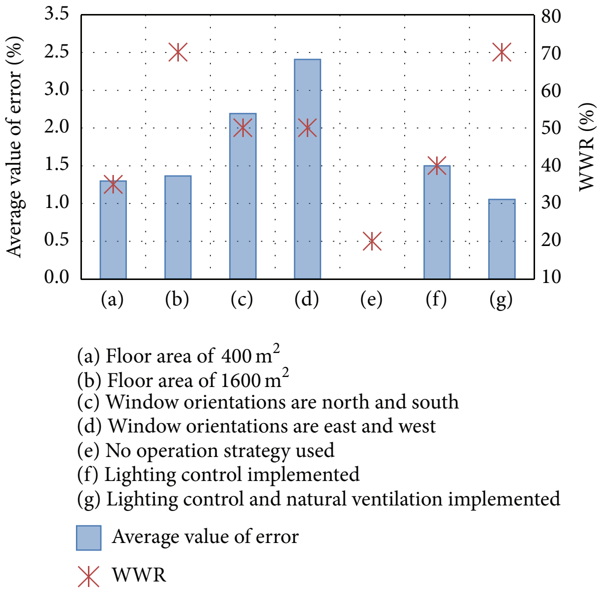


FIGURE 12: WWRs that produce a minimum average value of the error.

an appropriate strategy for reducing CO$_2$ emissions. Then, a modest WWR can be used as the default value. When both lighting control and natural ventilation are utilized, an increased window area tends to reduce CO$_2$ emissions. In this case, a large window area should be used as the default value. The installation of a ventilation tower could also be considered as a default input for an energy simulation because the natural ventilation effect does not saturate, even at the highest WWR. These results imply that the presence or absence of these operation modes must be included at the early stage of building design to increase the precision of the simulation at this stage.

5. Conclusions

To minimize the magnitude of the change in the default values, the default values should be chosen in accordance with the building design conditions, such as the building scale, location, and operation mode, including lighting control and natural ventilation. In this study, we first confirm that the ideal default values depend on the building design conditions. When a building scale and space depth are relatively small, each case has a different optimal WWR. The optimal window sizes vary depending on the climate condition and the building operation mode. However, for buildings with relatively large scales with large space depths, an increase in the window area is an appropriate strategy for any climate condition.

Then, we investigate the influence of each condition on the variation in the ideal default values for the WWR. These effects can be used to determine the types of building conditions that should be considered when selecting the ideal default values for a new building design project. In the case studies considered, the building scale and the space depth are found to have a large impact on the ideal default value of the WWR, whereas the window orientation has little impact. In addition, the presence or absence of lighting control and natural ventilation has a significant influence on the ideal default value. Thus, the operation mode must be chosen at the early stage of the building design because these elements are critical in determining the optimal window area.

This study focuses on the WWR because the value has a significant impact on the energy simulation results. The concept of an ideal default value can presumably be adapted to any input required for building performance simulations. In future studies, the author plans to apply the idea to other inputs, such as the inputs required for template files of standardized building properties [15].

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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Research Article

Translating Building Information Modeling to Building Energy Modeling Using Model View Definition

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This paper presents a new approach to translate between Building Information Modeling (BIM) and Building Energy Modeling (BEM) that uses Modelica, an object-oriented declarative, equation-based simulation environment. The approach (*BIM2BEM*) has been developed using a data modeling method to enable seamless model translations of building geometry, materials, and topology. Using data modeling, we created a Model View Definition (MVD) consisting of a process model and a class diagram. The process model demonstrates object-mapping between BIM and Modelica-based BEM (*ModelicaBEM*) and facilitates the definition of required information during model translations. The class diagram represents the information and object relationships to produce a class package intermediate between the BIM and BEM. The implementation of the intermediate class package enables system interface (*Revit2Modelica*) development for automatic BIM data translation into *ModelicaBEM*. In order to demonstrate and validate our approach, simulation result comparisons have been conducted via three test cases using (1) the BIM-based Modelica models generated from *Revit2Modelica* and (2) BEM models manually created using LBNL Modelica Buildings library. Our implementation shows that *BIM2BEM* (1) enables BIM models to be translated into *ModelicaBEM* models, (2) enables system interface development based on the MVD for thermal simulation, and (3) facilitates the reuse of original BIM data into building energy simulation without an import/export process.

1. Introduction

The exchange of data between building design representations and energy simulation representation has been a major challenge in the design process, resulting in the fact that building energy performance simulation is often omitted from the process [1]. The translation process is labor intensive, error-prone, and cumbersome [1–4]. Although tools have been developed to support the generation of an energy model from a design model, disconnections still exist between the various models [1, 5–7]. We speculate that many of the problems derive from building energy simulation tools that fail to take advantage of object-oriented programming (OOP) and do not easily allow for mapping from an object-oriented design model. To improve and enhance the model translation effectiveness, we investigated a new approach to link building information modeling (BIM), which is commonly used to support architectural design, to building energy modeling (BEM) that supports energy simulation. We used C# programming to directly access the object-oriented data representation within a BIM authoring system, and Modelica, an object-oriented physical modeling language to simulate the energy performance [8]. Our hypothesis is that use of object-oriented constructs within both BIM and BEM will enable more efficient and reliable translation and improve maintainability.

Our research has employed data modeling to develop *BIM2BEM* software to connect autodesk Revit to the Modelica Buildings Library [9]. In this paper, the *BIM2BEM* automatically generated BEM is called *ModelicaBEM*. It contains information derived from the BIM and can execute thermal simulation to obtain building performances such as indoor temperature and energy loads. We have developed *BIM2BEM* software to translate from the BIM to the *ModelicaBEM*. The objectives of our research are (1) to facilitate the reuse of original BIM data in building energy simulation without an import/export process; (2) to enable moderately complex multiple-zone BIM models to be translated into *ModelicaBEM*; and (3) to ease and facilitate further development through object encapsulation and provision of well-defined interfaces.

Our research process has been to use data modeling to create Model View Definitions (MVD) that consist of a process model and a class diagram and then conduct testing to assure that the translation works properly. We hoped to discover the effects and opportunities that arise. The following four phases have been conducted for the MVD development.

(1) Develop a process model to document the mapping from BIM to BEM.
(2) Develop class diagrams to represent the required information and object relationships.
(3) Implement the translation classes to support BEM model creation using BIM data. We refer to this as the *BIM2BEM* software.
(4) Conduct tests to demonstrate and validate the *BIM2BEM* approach.

The objectives of *BIM2BEM* are (1) to enable multiple-zone BIM models to be translated into *ModelicaBEM* models, (2) to enable system interface development based on the MVD for thermal simulation, and (3) to facilitate the reuse of original BIM data in building energy simulation without an import/export process.

The research scope is confined to translating the building envelope information of BIM, including geometry, material, and topology of a building model. In this paper, the Modelica-based BEM models translated from BIM models are called *ModelicaBEM* that contain BIM information and can execute thermal simulation to obtain building performances such as indoor temperature and energy loads. The terms "Building Information Modeling" or "Building Information Model(s)" are used interchangeably in different contexts and are abbreviated as BIM.

2. Background and Problems

Studies have presented the value of reusing data that has been produced by building designers when creating building energy models [1, 2, 6, 7, 10]. To increase the usability of data from designers in building energy simulation, various research prototypes [1, 2] and commercial products have been created, such as Green Building Studio.

However, reliably generating high quality BEM using current tools remains difficult. Although much of the process has been automated, intervention by the user to simplify models, choose among representations with subtle differences, and correct errors is still needed. For example, the users of Green Building Studio, which is a web-based energy analysis tool working with Revit (a BIM authoring tool developed by Autodesk), must finish the model check process to create a reliable gbXML file. Current energy simulation engines have their own unique input formats consisting of nonobject-oriented text files with highly specialized syntax and semantics [7]. The different data structures between BIM and an energy simulation engine often prevent efficient data translation or exchange. For instance, a translation process is required to perform data exchange through standard data schemas, which hinders the utilization of the parametric modeling capability of BIM in the design process. While a limited number of energy simulation tools support standard schema-based model translation, the absence of a standard interface in the tools also requires additional efforts and understanding of simulation processes for architects and designers to obtain building analysis results [7, 11, 12].

The efficient and effective data translation between BIM and building energy simulation can be achieved when two domains have the same modeling method such as an object-oriented method. A comprehensive data exchange model can then support direct mapping between them and facilitate an easy-to-use user interface implementation.

Based on the development of an interdisciplinary data exchange model and implementation of the model for direct mapping without an import/export process, *BIM2BEM* can facilitate the reuse of data from BIM in building energy simulation.

3. Research Objectives

This section describes challenges and tasks, tools and data, and methodology for *BIM2BEM* development. The *BIM2BEM* software is intended to handle the translation from a BIM to BEM represented in Modelica to facilitate executing a simulation with the Modelica Buildings toolkit.

3.1. Challenges.

3.1. Challenges. The main challenge of the project is to facilitate seamless model translation, requiring less manual data conversions between BIM and *ModelicaBEM*.

To achieve effective and efficient model translation, the following tasks need to be completed: (1) defining an object mapping process between BIM and *ModelicaBEM* to identify required information, (2) representing the identified datasets for the object mapping process, and (3) implementing the represented data subset and object relationships in a Modelica-based simulation tool.

3.1.1. Define an Object Mapping Process between BIM and ModelicaBEM. Object semantics and relationships in architectural models are often represented differently than in the energy models. For example, in energy modeling building components are abstracted as 2D surfaces in order to enhance simulation performances, while the components are presented as 3D geometry in BIM.

To facilitate consistent object semantics and relationships between BIM and *ModelicaBEM*, an object mapping process needs to be conducted. The object mapping process demands to identify what information BIM and *ModelicaBEM* should be able to exchange. We utilized a data model method to classify mismatched object semantics and behaviors for the object mapping. The data modeling enables maintaining consistent object classifications of building components from BIM to *ModelicaBEM*.

3.1.2. Represent Datasets for Object Mapping Processes. Different object semantics and relationships between BIM and *ModelicaBEM* demand their own data structure. For instance, data for building components such as walls, floors, and roofs are represented as 3D solids in BIM, whereas the same data are considered as surfaces in *ModelicaBEM*. In addition, a room object in BIM is represented as a zone in BEM, and the topology information for boundary condition is only represented in BEM, which can be retrieved by the combination of building objects information from BIM. To map the mismatched objects and behaviors, a data representation process is needed regarding what datasets in BIM and *ModelicaBEM* are used.

3.1.3. Implement the Datasets and Object Relationships. The datasets and object relationships need to be created in a Modelica using parameters and functions. Instantiated objects can present building and related energy components of *ModelicaBEM*. For example, the area parameter can represent diverse geometry instead of just rectangular shape. Building topology in BIM can be mapped into *ModelicaBEM* topology, and calculated area information from BIM can be stored through a parameter.

3.2. Tools. For the *BIM2BEM* development, we used the BIM authoring tool Autodesk Revit and its application programming interface (API), and the LBNL Modelica Buildings Library [9].

3.2.1. BIM Authoring Tool (Revit) and Its API. BIM supports three-Dimensional, semantically rich, and parametric modeling for design and construction during a building's lifecycle [13, 14]. BIM tools represent such a capability through their own data structure and implement the structure using specific database schema [13–15]. The BIM tools allow the databases to be represented as standard data models such as Industry Foundation Classes (IFC, a standard data schema for exchanging data among different applications) through user commands or API [16–18]. Software developers can access specific building component data of Revit and create a comprehensive database through API using the C# language [19]. In our project, instead of using standard data models such as IFC or gbXML, we utilized the Revit API capability to access the BIM data directly to (1) preserve object relationships established by parametric modeling, (2) define a model view of Revit to support bidirectional data exchange with the object-oriented simulation solver—LBNL Modelica Buildings Library.

3.2.2. Modelica and Dymola. To support modeling and simulation from a physical point of view, object-oriented physical modeling (OOPM) has been developed to offer a structured and equation-based modeling approach [20, 21]. Modelica is an OOPM language and enables users to model the complex design of mechanical, electrical, and control systems using differential algebraic equations of relevant physics laws [21]. Modelica can represent topology of energy models using components and object connection diagrams [21]. Such capabilities can facilitate an object mapping from the BIM structure to *ModelicaBEM* naturally. Modelica libraries such as LBNL Modelica Buildings Library [9] facilitate the use of Modelica in thermal simulation, offering model components and solvers. We used Dymola [22] as an integrated simulation environment for Modelica models with LBNL Modelica Buildings Library as the thermal simulation engine.

3.2.3. LBNL Modelica Buildings Library. The LBNL Modelica Buildings library has been developed for building energy simulations to support the simulation of heating and cooling system, controls, heat transfer through building envelopes, and airflow [23]. One of the major resources for building thermal analysis in the library is the HeatTransfer and Room packages, which have been validated through benchmarked simulation models [24, 25]. The validation accounts for the capability of whole building simulations [24].

In order to create *ModelicaBEM* that can use the LBNL Modelica Buildings Library for building thermal simulation, Modelica code must be created based on BIM data. Insufficient data exchange capability between BIM and the library results in the designers' subjective interpretations of building data and human errors in creating *ModelicaBEM*. In addition, the absence of a de facto standard interface for the data exchange causes a difficulty in translating BIM into *ModelicaBEM* incorporating with the library. *BIM2BEM* facilitates the data exchange through the model view of the library and the intermediate classes.

3.3. Methodology and Tasks. Our methodology in the *BIM2BEM* development includes (1) developing an MVD through data modeling, (2) implementing the designed classes in the MVD using the Modelica and the C# language, and (3) conducting test cases for validation by simulation of result comparisons for multizone models.

3.3.1. MVD Development. We utilized a data modeling method to develop an MVD for data exchange between BIM and *ModelicaBEM*. The MVD consists of (1) modeling the process to map objects and overcome mismatched objects' semantics and behaviors and (2) designing classes to represent the required information and object relationships.

(1) Process Modeling. The process of interest in our research is the mapping from BIM to BEM. We used process modeling to identify required information and object relationships. Although some data can be easily translated, the challenges arise from recognizing mismatched object semantics and behaviors between the BIM and the BEM. From the investigation of architectural modeling and building energy modeling, we can distinguish the mismatches into (1) semantic mismatches of building components and (2) behavior mismatches between BIM and BEM. Resolving these mismatches was a major task in this research.

Semantic mismatches hamper data exchange of objects and parameters because the starting representation and the ending representation make use of fundamentally different abstractions. For example, BIM represents a building envelop by composing building components such as walls, floors, and roofs, while BEM represents the envelope as exterior and interior surfaces. In order to map the building components into exterior surfaces, the required information can include the area of the surfaces and the summation of them through a function. To implement the function, the object relationships between related building components need to be defined to inform what kind of and how many surfaces constitute the whole exterior surface.

Behavior mismatches occur when the objects are similar or identical in BIM and BEM, but the behavior of the object is different. The required information must be derived by applying a rule that accepts the BIM information as input and produces the BEM information as output. For example, when a user separates two rooms by using an interior wall in BIM, BEM defines the boundary conditions to facilitate heat transfer between the separated rooms. We can establish a rule: if one surface of the wall object in BIM is defined as a *surface boundary*, the other surface can be a *construction boundary* automatically to map the boundary condition into BEM. BEM defines the two boundary conditions to calculate heat transfer on interior walls between thermal zones. We can apply the rule in generating *ModelicaBEM*'s building topology. The boundary condition information can be obtained by implementing the rule using a room object and building components enclosing the room such as walls, floors, and roofs.

The process modeling method involves decomposing the process into a series of activities, connecting them into a logical sequence, and collecting the data requirements [26, 27]. We used process modeling to identify the required information and object relationships and support more efficient workflows [28]. The process model can be then used in defining the scope of data modeling.

There are several graphic and nongraphic methods for process modeling, such as the Flowchart, unified modeling language(s) (UML), and IDEF0 [29]. IDEF0 (integrated definition of functional modeling) is most commonly used in product data modeling [30]. We used IDEF0 to describe how activities for the mapping are connected, ordered, and structured. The unique feature of IDEF0 models is its ICOM codes (Input, Control, Output, and Mechanism presented by arrows): Input and Output arrows represent the data and object flows into and out of a function; Control arrows indicate the required conditions for a function; and Mechanism arrows denote the means to performing a function [31]. IDEF0 models are especially useful in understanding a data flow [32]. We created an IDEF0 diagram for the process model and then defined additional information that is needed to map data between BIM and *ModelicaBEM*. The information will be represented through a class diagram including attributes and class relationships. Section 4 explains how requirements for object mapping can be represented using IDEF0 specifications.

(2) Class Design. We developed a class diagram to represent specific data types and object relationships as objects and relationships. Based on the investigation of the mapping process for the required information and object relationships, we created two model views to define datasets: Revit Model View and Modelica Model View. Based on the two model views, we created an intermediate class package consisting of wrapper classes and interface classes as an Exchange Model View.

The class diagram enables *ModelicaBEM* not only to follow the data structure and semantics of BIM but also to represent related information for thermal simulation. The following section describes how to create the class diagram using UML.

3.3.2. Implementation. We used the C# language to implement the functions in the interface classes, which facilitate data transformations such as building topology translation.

We used wrapper classes in Modelica to bridge between the Revit BIM classes and the energy model classes in the LBNL Modelica Buildings library.

The wrapper classes enable *ModelicaBEM* to populate instantiated objects. Consequently, a *ModelicaBEM* is able to represent mismatched semantics and behaviors by composing related instances and parameters that store the values from BIM. *ModelicaBEM* rely on a system interface that can preprocess BIM to prepare the required information and assemble the instantiated objects before the *ModelicaBEM* reaches the LBNL Modelica Buildings Library. The interface classes enable *Revit2Modelica* to preprocess BIM.

3.3.3. Conducting Test Cases and Simulation Result Comparisons. Three test cases have been studied to demonstrate and validate the *BIM2BEM* approach. For demonstration, a prototype shows how multi-zone BIM models can be automatically translated into *ModelicaBEM*. In case of validation, the simulation result comparisons are conducted between two BEM models in each test case: one is automatically generated *ModelicaBEM* and the other is the manually created model following LBNL's BEM structure.

4. *BIM2BEM* Development

BIM and LBNL's BEM (manually created using Modelica) follow object-oriented modeling concepts; however, they have different object semantics and behaviors, which are challenging for model translation. In this project, we developed an MVD to define data exchange requirements for Revit and the LBNL Modelica Buildings Library.

MVD usually defines the subset of IFC models for supporting data interoperability [33]. We adopted the concept of MVD to reduce the interoperability problem and support more seamless translation between BIM (Revit) and *ModelicaBEM*. The MVD development follows a modeling-diagramming-implementing approach: (1) developing a process model to identify building objects and their relationships, (2) creating a class diagram based on application model

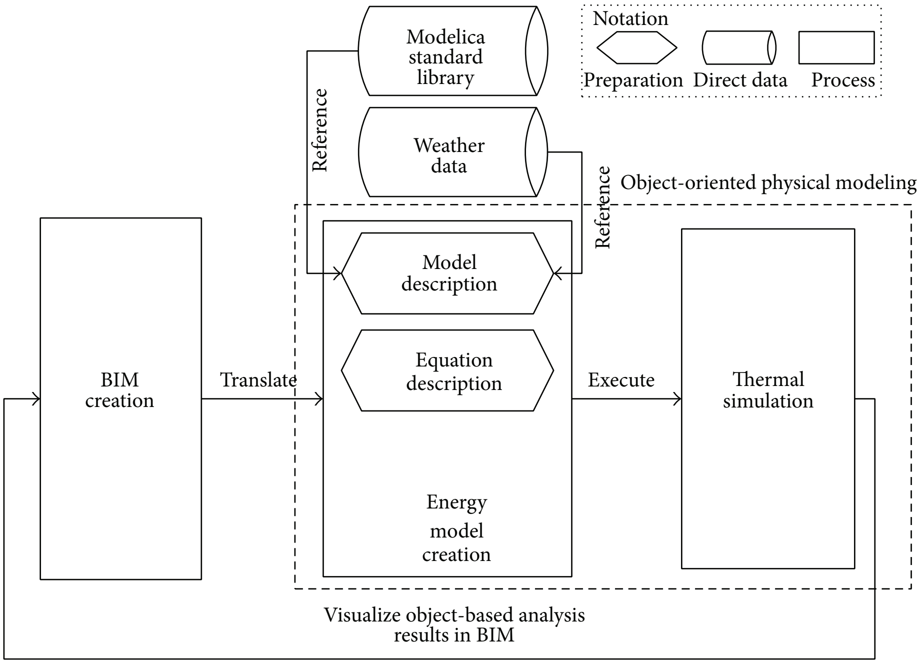


FIGURE 1: The overall translation process between BIM and *ModelicaBEM*.

```
Buildings.Rooms.MixedAir mixedAir(
  redeclare package Medium = MediumA,
  AFlo=32,
  hRoo=3,
  nConExt=6,
  datConExt(
    layers={matLayRoo,matLayFlo,...},
    A={32,32,...},
    til={Buildings.HeatTransfer.Types.Tilt.Ceiling,Buildings.HeatTransfer.Types.Tilt.Floor,...},
    azi={Buildings.HeatTransfer.Types.Azimuth.S,Buildings.HeatTransfer.Types.Azimuth.N,...}),
  nConExtWin=0,
  nConPar=0,
  nConBou=0,
  nSurBou=0,
  linearizeRadiation=false,
  enegyDynamics=Modelica.Fluid.Types.Dynamics.FixedInitial,
  nPorts=1,
  lat=0.73268921998722)
```

ALGORITHM 1: A code block for thermal zone modeling in LBNL Modelica Buildings library.

views and the exchange model view, and (3) implementing the intermediate class package.

4.1. Develop a Process Model for Translations. To identify mismatched objects semantics and behavior, we studied the translation process between BIM and *ModelicaBEM*. Figure 1 shows the overall process of how BEM is incorporated with BIM: data from BIM are translated into *ModelicaBEM*, and *ModelicaBEM* produces object-based results after completing the simulation, which are able to be displayed in BIM finally [34].

The data translation mainly occurs between BIM Creation and Energy Model Creation shown in Figure 1. The model description preparation in the Energy Model Creation activity is to populate required information from the Modelica standard library and the weather data. The major classes and parameters in LBNL Modelica Buildings Library are shown in Table 1. The boundary condition definition in the library has five types: exterior opaque surfaces (datConExt), exterior opaque surfaces with windows (datConExtWin), interior walls between thermal zones (datConBou or surBou), and interior partitions in a thermal zone (datConPar). We applied the translation rules (in Section 4.3) for translating the building topology into the boundary conditions.

The building can be represented with instances from the classes in Modelica using LBNL's library. As shown in Algorithm 1, a thermal zone consisting of six surfaces without

Table 1: Classes and parameters adapted from LBNL Modelica Buildings library [9].

Classes	Object properties	
	Name	Description
MixedAir models a room with completely mixed air for heat transfer through a building envelop. The room consists of any number of construction types and surfaces for heat exchange through convection, conduction, and infrared radiation and solar radiation.	Medium	The medium information of a room air such as gas, most air, and dry air.
	aFlo	The floor area attached to a room.
	hRoo	The roof area attached to a room.
	datConExt	Opaque surfaces.
	nConExt	Number of datConExt.
	datConExtWin	Opaque surfaces with windows.
	nConExtWin	Number of datConExtWin.
	datConPar	Interior partitions in a thermal zone.
	nConPar	Number of datConPar.
	datConBou	Opaque surfaces on interior walls between thermal zones.
	nConBou	Number of datConBou.
	surBou	Opaque surfaces on the same interior walls between thermal zones.
	nSurBou	Number of SurBou.
	nPorts	Number of ports that constructs equations to simulate physical processes.
	Latitude	Latitude information of a room.
	energyDynamics	The information of fluid types in networks of vessels, pipes, fluid machines, vales, and fittings.
	linearizeRadiation	A setting value whether to linearize emissive power or not.
Opaque constructions describe material definitions for constructions with one or more layers of material.	matLayExt	Construction material for exterior walls.
GlazingSystem describes thermal properties for glazing systems.	nLay	Number of glass layers.
	haveExteriorShade	A setting value whether a window has an exterior shade or not.
	haveInteriorShade	A setting value whether a window has an interior shade or not.
	Glass	Thermophysical properties for window glass.
	Gas	Thermophysical properties for window gas fills.
	uFra	U-value of frame.
	absIRFra	Infrared absorptivity of window frame.
	absSolFra	Solar absorptivity of window frame.
DoorDiscretizedOpen describes the bidirectional airflow through an open door.	Medium	The medium information of the room airflow through an open door.
	Width	Width of opening
	Height	Height of opening

any openings can be declared as a thermal zone instance (line 1) and surfaces information is given parameters of the zone instance. Six surfaces of the thermal zone are categorized as opaque surfaces (line 5), and their layer information (line 7), area (line 8), a tilt angle (line 9), and an azimuth angle (line 10) are provided.

LBNL Modelica Buildings Library is developed based on engineering-semantic point of view. As shown in Algorithm 1, the thermal zone instance does not require any wall instances to simulate a room model even though the building consists of several walls. Such mismatched object semantics (compared to BIM) require us to define an object semantics rule set to represent information in BIM for the BIM-to-*ModelicaBEM* translation. Based on the investigation and the guideline for object mapping [35], we set the rule set as follows.

(i) *Addition*: adding missing data in BIM that are required for *ModelicaBEM*, such as solar and infrared absorptivities, solar transmittance, and infrared transmissivity of glass.

(ii) *Translation*: data translation between BIM and *ModelicaBEM* to represent mismatched semantics, such as rooms to thermal zones.

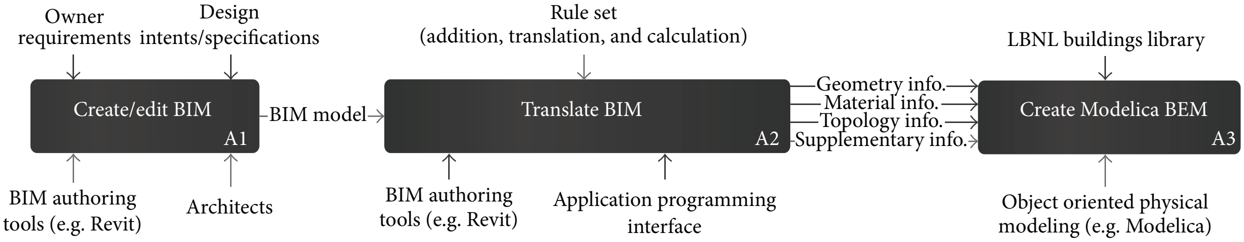


Figure 2: A process model of BIM-to-*ModelicaBEM* translation using IDEF0.

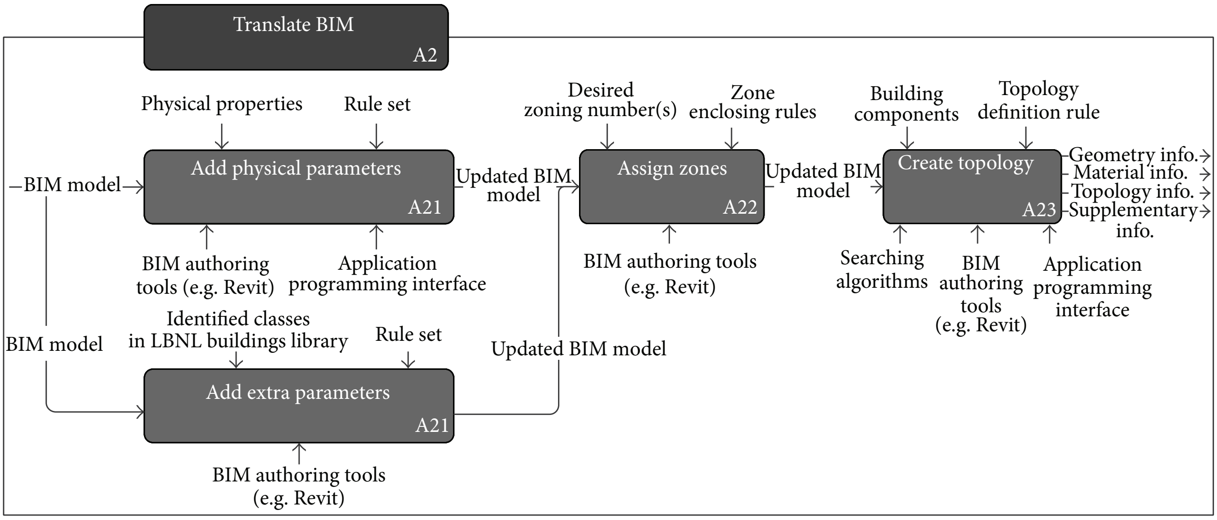


Figure 3: Detailed process model of translate-BIM activity to represent required data flow.

(iii) *Calculation*: calculating new values using existing values in BIM, such as window-frame ratio and construction boundary types.

We can identify required processes applying the rule set to *ModelicaBEM* creation and represent the BIM-to-*ModelicaBEM* translation using IDEF0 as shown in Figure 2.

However, the Translate BIM activity only represents object semantics. As described in Section 3.3; the LBNL Modelica Buildings Library also represents object behaviors including building topology differently. To represent such mismatched behaviors, we identify detailed processes of the Translate BIM activity as shown in Figure 3.

Figure 3 shows the data flow of the Translate BIM activity including topology creation. The information in each step is considered as the requirements for the data model and they will be made into classes. Based on the processes and a mapping guideline [35], we defined the requirements from each step as shown in Table 2.

The data requirements in Tables 1 and 2 can be represented as classes and properties in a class diagram. The class diagram will also represent object behaviors via defined functions and relationships among classes.

4.2. Create Class Definitions. The class diagram contains classes, including properties and functions, and class relationships in application model views and the exchange model view.

The model views represent what the specific data and datasets are for the data requirements from the process models in Revit and LBNL Modelica Buildings Library (Revit Model View and Modelica Model View). The Exchange Model View consists of wrapper classes and interface classes and allows *ModelicaBEM* to hold building geometries, material properties, and topology for thermal simulation.

4.2.1. Application Model Views

(1) Revit Model View. Revit models contain architectural data created by the users. Very large data sets can be represented in BIM; however, only part of the data is applicable to thermal simulation. The data for thermal simulation are represented as native Revit instances of classes and relationships shown in Figure 4. These classes can represent the data requirements categorized in Table 2. The description of the classes is adapted from Autodesk references [19]. Based on the

Table 2: Defined steps and required data.

Steps	Description	Data requirements
Create/edit BIM	Architects can create building components such as walls, floors, roofs, doors, and windows to represent their design intents and specifications in Revit.	(i) Geometry information: area, tilt, azimuth, height, and width. (ii) Material information: thickness (iii) Supplementary information: project location, identification numbers for each building components.
Define physical parameters and extra parameters	In order to map missed physical properties in Revit into LBNL Modelica Buildings library, we defined the step of adding the physical parameters, e.g., solar and infrared absorptivities, in existing material properties in Revit. The physical parameters are added through Revit API. Additional information regarding the glazing system for thermal modeling needs to be prepared in Revit. The properties for glass thickness and ratio of window frame can be added via updating the window family, and parameters for material properties, e.g., solar transmittance, can be added by using Revit API.	(i) Additional material information: thermal conductivity, specific heat capacity, mass density, and solar and infrared absorptivities (ii) Additional thermal information for glazing system: glass thickness, the ratio of window frame (iii) Additional material information for glass: solar transmittance, infrared transmissivity of glass, solar reflectance of surface, U-value of frame, infrared and solar absorptivity of window frames
Assign zones	To conduct room-to-thermal zone translation, zoning information is required in Revit. We defined thermal zones by using room components in Revit. The room components basically contain the information of height and the area attached to floors. The latitude information for the room can be retrieved from a Revit function.	(i) Room information: height, area of floors, and latitude (ii) Zoning information: latitude
Create topology	The thermal information for heat transfer of the building envelope can be prepared in Revit: the information of how the building envelope is constructed, e.g., boundary condition types, and the number of ports for thermal network connections in *ModelicaBEM* can be generated based on the building topology information retrieved using Revit API. The building topology provides the information of how many and what building components are connected to a room. The information will be the values of the boundary condition variables in a MixedAir instance in *ModelicaBEM*.	(i) Thermal information: boundary condition types and the number of ports (ii) Building components information

description, we created a class diagram (Figure 4) using a UML Class Diagram to show the relationships among the classes [36].

(i) *Revit.Element*: the *Element* class represents geometry information of building components such as area, height, length, and volume through relationships with *Revit.Parameter* class. Such inherited classes from the *Element* class, for example, *Wall, Floor*, and *Roof (Base)* can have the geometry information.

(ii) *Revit.Wall*: the *Wall* class, derived from the *Element* class, has additional geometry information derived from the *Element* class such as orientation and width information. Also, the type information of a wall can be defined through *WallType* class.

(iii) *Revit.RoofBase*: the *RoofBase* class provides additional information such as the roof types. The type property can categorize roof instances with specified purposes such as flat roof or slope roof.

(iv) *Revit.Floor*: the *Floor* class is inherited from the *CeilingAndFloor* class that provides support for all ceiling and floor objects including geometry information. This *Floor* class has an additional type property representing floor types.

(v) *Revit.FamilyInstance*: the *FamilyInstance* represents a single object of a family type such as doors and windows. If a door is created in a wall between two rooms, the connectivity information regarding which room is connected to another can be defined via the properties, *fromRoom* and *toRoom*. The *FamilyInstance* has a relationship with *FamilySymbol*, which enables additional parameters to represent thermal properties such as the frame ratio information. For example, a window family allows creating a thickness parameter to calculate the frame ratio. The parameters are represented through the *FamilySymbol* class, and the *FamilyInstance* class represents a window object.

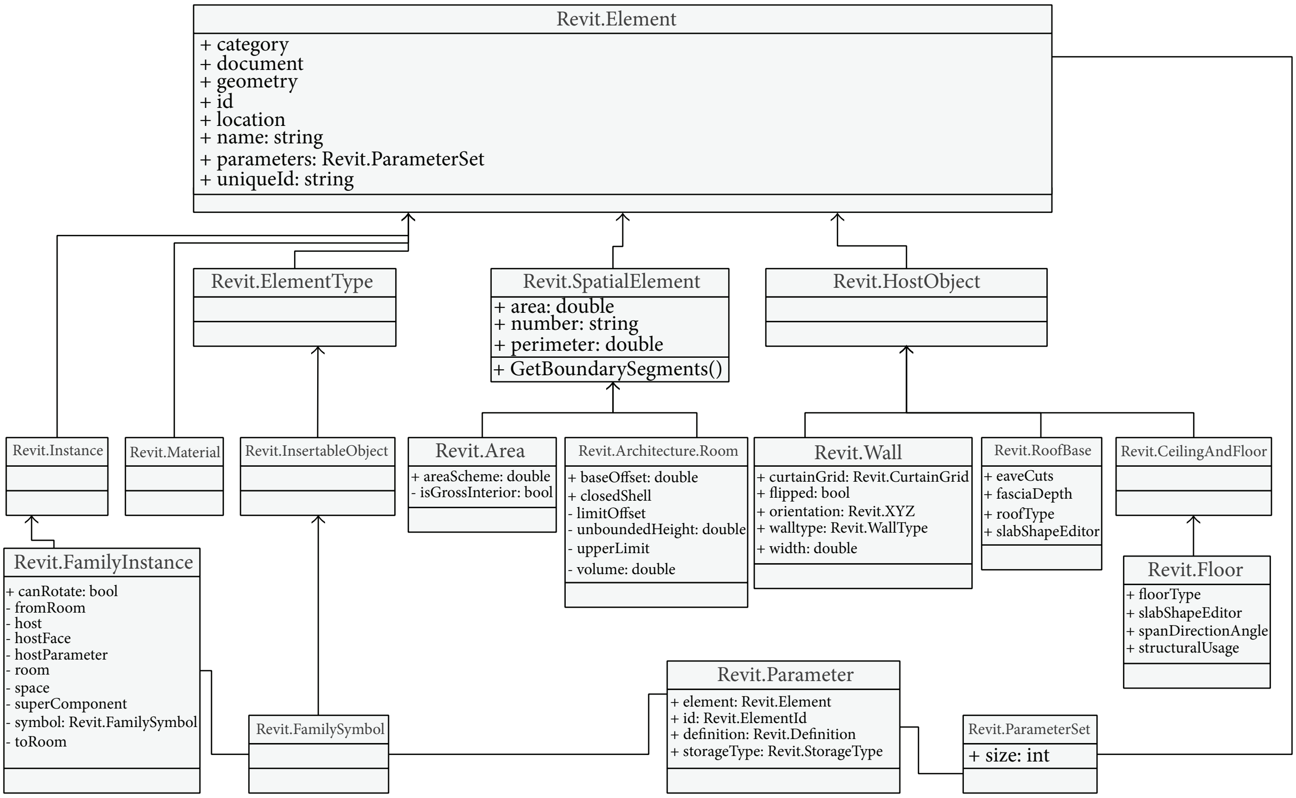


Figure 4: Class diagram of the Revit model view.

(vi) *Revit.Architecture.Room*: the *Room* class represents the basic information such as area, height, and perimeter inherited from the superclass (*SpatialElement*). The volume information of a room is only defined in the *Room* class. Such a relationship provides access to retrieve required information after a room instance is created.

(vii) *Revit.Material*: the *Material* class represents material information regarding the color of the material, the name of general material types, the shininess and smoothness of the material, and so on. The category property in this class enables building components to access their material information, that is, once a wall instance is created, the instance has parameters including a material instance.

Using the objects described in this class diagram, the steps of "Create/Edit BIM," "Add extra parameters," and "Assign zones" in the process model can be defined. "Add physical parameters" can be composed through functions in the interface classes.

(2) Modelica Model View. We created a Modelica model view to represent the information identified in Table 1. The model view shows the classes and relationships that are defined to create a model using the LBNL Modelica Buildings library. The classes are MixedAir, GlazingSystem, DoorDiscretizedOpen, FixedBoundary, WeatherData, and additional Modelica standard classes.

Figure 5 shows the data subsets in LBNL Modelica Buildings Library as classes and relationships. For example, in the model description code block (Algorithm 1), the mixedAir object is instantiated from the MixedAir class under the Rooms package (Rooms.MixedAir), and the properties in the object are declared in another MixedAir class under the BaseClasses (BaseClasses.MixedAir). LBNL Modelica Buildings library defines the relationship between the two classes: the BaseClasses.MixedAir object is encapsulated as a parameter object in the Rooms.MixedAir object.

We used the UML specifications to represent the classes in Figure 5 based on our investigation of LBNL Modelica Buildings Library.

4.2.2. Exchange MVD.

We created an Exchange MVD to define interface and wrapper classes. The Exchange Model View integrates two different semantic models, which represent not only architecture but also engineering points of view. For example, the wall class has a material instance parameter and a different material type in the Modelica model, and the property of the wall instance such as area can be passed to the Modelica model. The room class has wall instances to pass material and area information to parameters in MixedAir class.

(1) Wrapper Classes. Wrapper classes allow *ModelicaBEM* models to follow object semantics of Revit and to utilize LBNL Modelica Buildings library. Wrapper classes adopt the

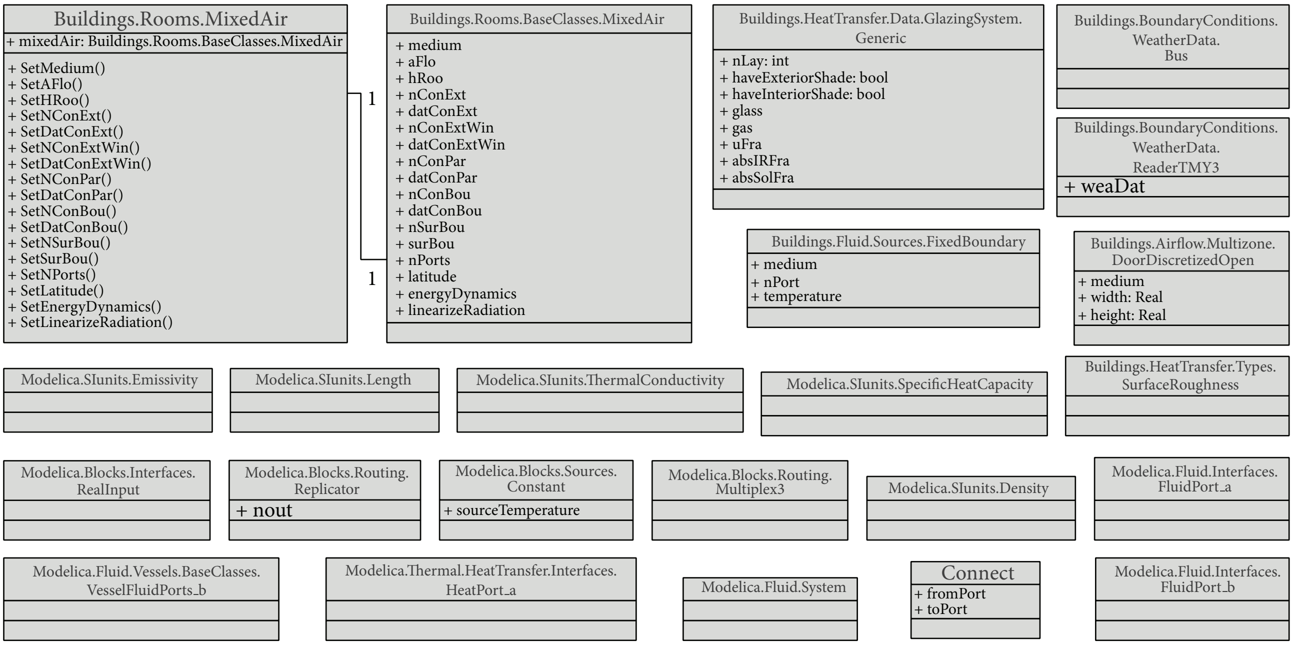


Figure 5: Class diagram of the Modelica model view.

following rules, which represent a common object relationship among building objects.

(i) A building object in Revit consists of room objects, walls, floors, and roofs enclosing the room.

(ii) A room object in Revit is transformed into a single thermal zone object (MixedAir object in LBNL's BEM). A multi-zone model can be created through connecting multiple room objects.

(iii) Topology for energy modeling can be translated from the connectivity of the Revit building components.

Based on the rules, wrapper classes include *Wall*, *Floor*, *Roof*, *Window*, *Door*, and *Room* classes. The instances from the classes enable the building component information to be transformed from BIM to *ModelicaBEM*.

Figure 6(a) shows the wrapper classes containing a series of properties that can transfer Revit parameters into *ModelicaBEM*. The relationships represent the rules. For example, the *BIM2BEM.Room* class has relationships with *BIM2BEM.Wall*, *BIM2BEM.Floor*, and *BIM2BEM.Roof* classes to represent the composition of a building object.

To differentiate class names between the application model views and wrapper classes, we specified the class name by starting with domain name; for example, the material class names in Revit and the wrapper classes are *Revit.Material* and *BIM2BEM.Material*, respectively. The wrapper classes are described below.

(i) *BIM2BEM.Room*: the *Room* class represents a single-zone model and wraps the *MixedAir* class of LBNL Modelica Buildings library in it. The MixedAir class models a room filled with mixed air. The MixedAir model and the library have been validated [9, 24, 25, 37]. The class properties and functions enable *ModelicaBEM* to populate required information such as building materials and components and thermal boundary conditions. For example, area, tilt, and azimuth as parameters are created in a room object.

(ii) *BIM2BEM.Wall*, *BIM2BEM.Floor*, and *BIM2BEM.Roof*: these classes store the basic building component information from BIM including area, tilt, azimuth, and material layers for energy modeling. The material layer information is represented as a parameter of a *BIM2BEM.Structure* instance. The defined relationships between the Room class and the building components classes enable each instantiated building object to be encapsulated in a room object to pass the geometry information.

(iii) *BIM2BEM.Window*: the *Window* class represents window geometry data as well as the data of glass panels and window frames in the Modelica model view. The *Window* class can represent material information by defining GlazingSystem.Generic instance as a parameter.

(iv) *BIM2BEM.Door*: the *Door* is a wrapper class of the *DoorDiscretizedOpen* class and consists of geometry properties such as width and height for calculating multizone airflow. Currently, we implemented a closed door to calculate heat transfer and infiltration through the door. A port property represents room-door-room connection as a parameter.

(v) *BIM2BEM.Structure* and *BIM2BEM.Material*: the *Structure* and *Material* classes are designed to represent material properties and geometry information of opaque constructions and how materials are

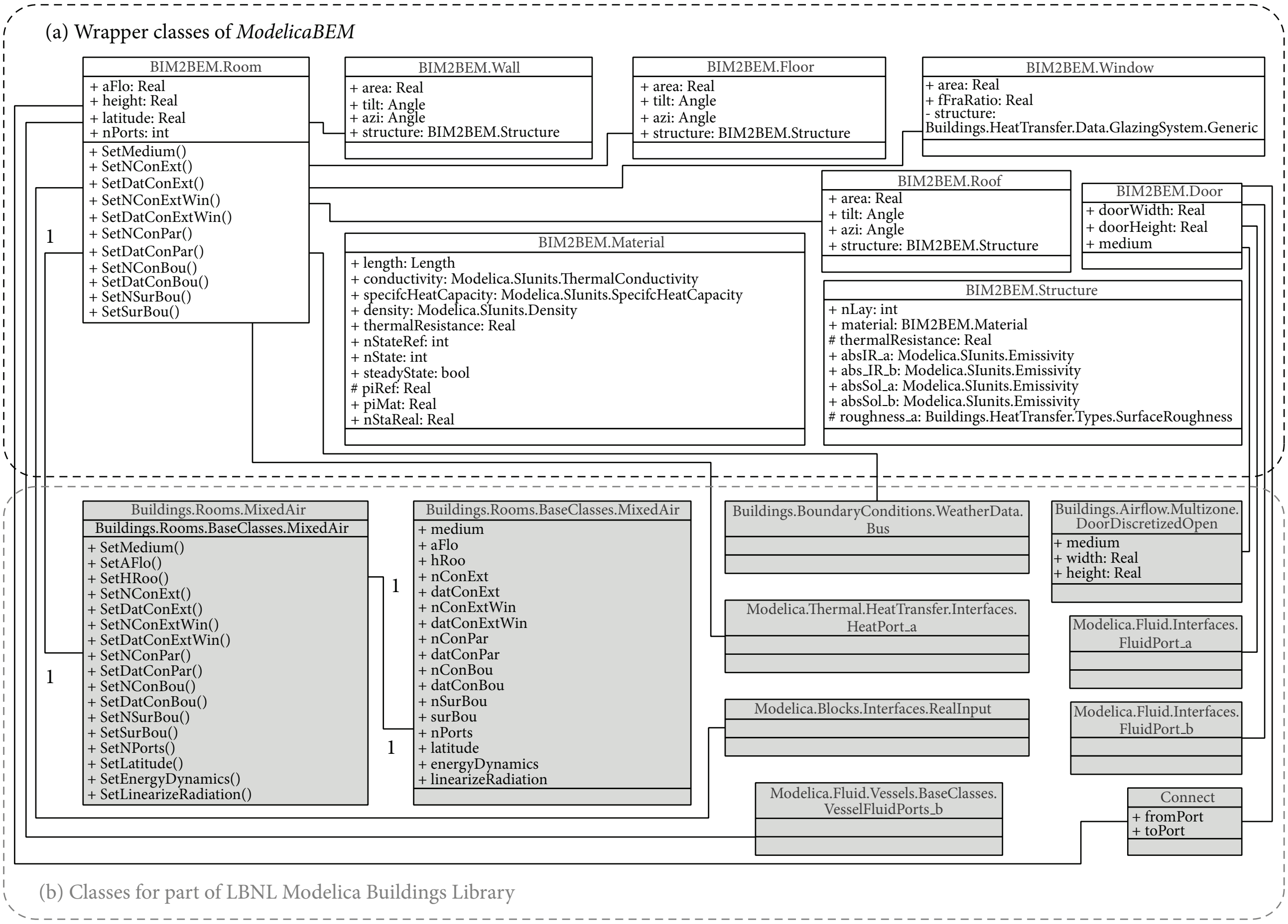


Figure 6: Class diagram of the wrapper classes.

assembled. The *Structure* class contains construction information with the number of layers where each layer is represented by *Material* instances. The Material class represents thermal information such as thermal conductivity, heat capacity, and density. The additional thermal properties for inner and outer surfaces such as solar and infrared absorptivities exist in the *Structure* class.

(2) Interface Classes. The interface classes are as shown in Figure 7.

The methods in the interface classes enable *ModelicaBEM* to contain object instances following Modelica language specifications. The following classes present the functions and object relationships in *ModelicaBEM*.

(i) *ModelicaBIM*: the *ModelicaBIM* class has functions to populate a *ModelicaBEM* model, which consists of three parts: building model description, energy components, and connections. The relationships in Figure 7 show the composition (e.g., the building model description is represented with composition relationships among the classes in the wrapper classes).

The functions enable the *ModelicaBEM* objects to instantiate the classes. For example, the *GetMaterialInstances()* function instantiates the *BIM2BEM.Material* class to present related materials in the building model description. As shown in Figure 7(d), eight functions map building envelope data, boundary conditions, and room geometry information from Revit to wrapper classes. In addition, two functions are defined to describe energy components and connections. For example, the energy object from the *WeatherData* class provides selected weather information to the *ModelicaBEM*; the information of selected geographical location is retrieved from Revit by the user's setting of the building location.

(i) *BIMtoModelica*: the *BIMtoModelica* class has two functions to support the *ModelicaBIM* class having relationships with Revit classes as shown in Figure 7(b). The two functions are implemented using Revit API. The *AddPhysicalParameters()* function allows a Revit model to include missing physical properties defined in Table 2. The specific values of boundary conditions in a Room instance can be computed through the *GenerateBuildingTopology()* function, which provides the boundary condition type information and generates building topology from an extended BIM.

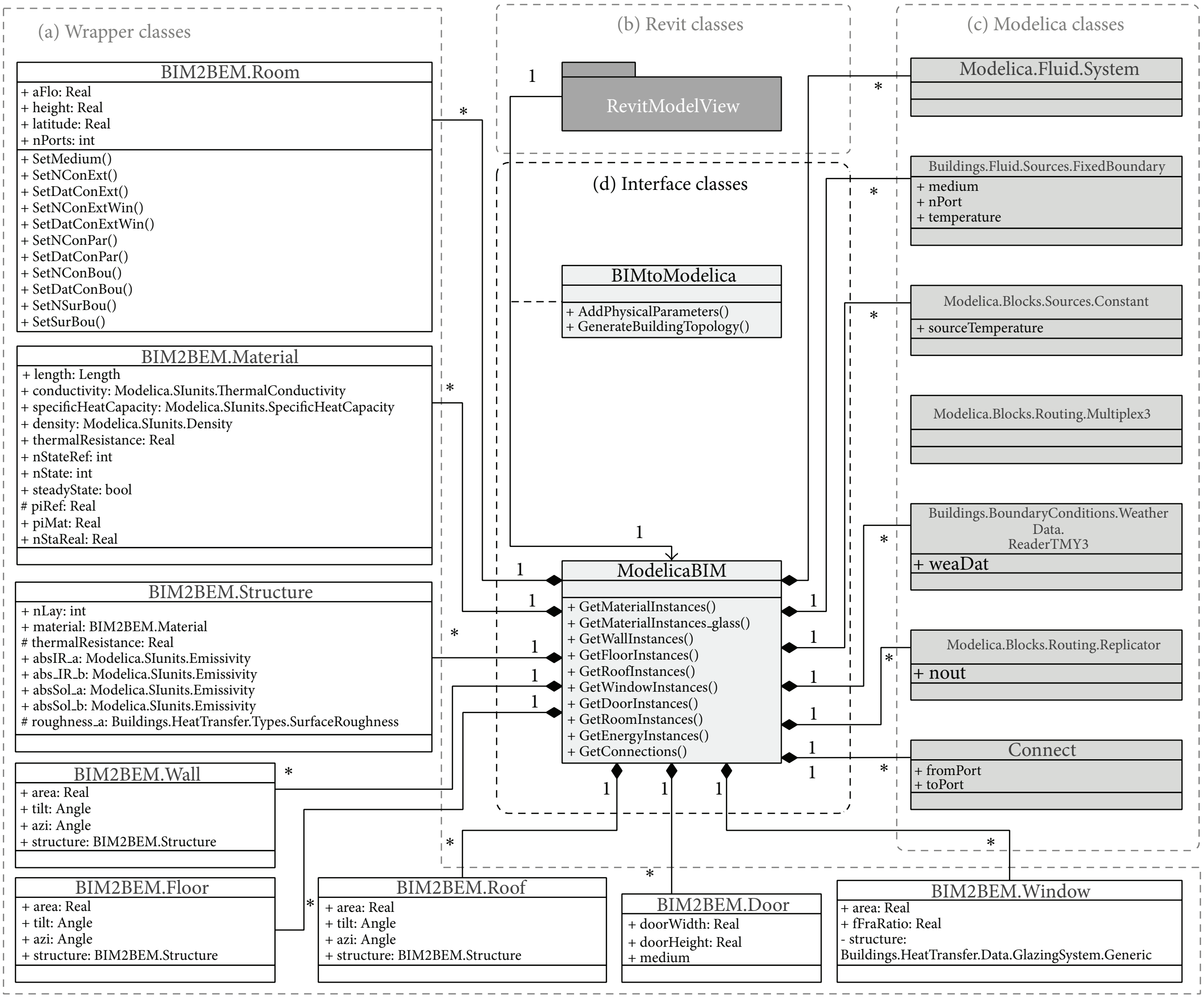


Figure 7: Class diagram of the interface and wrapper classes.

A detailed example of creating *ModelicaBEM* through the interface classes will be explained in the following section.

4.3. Implement Wrapper and Interface Classes. *ModelicaBEM* can be created with the implementation of the classes of the wrapper and interface.

The implementation of the wrapper classes is accomplished using Modelica language specifications. Algorithm 2 shows the implementation consisting of four declaration sections: Property, Wrapper component, Energy component, and Connect declaration. The Property declaration demonstrates how defined properties in *BIM2BEM.Room* class can be implemented using Modelica. The Wrapper and Energy component declarations represent the object relationships between the Room class and the connected classes. The Connect declaration implements connectors that represent a physical flow between the wrapper components and the energy components. Based on the implementation, the class package can act as a template when creating new instances.

The interface classes' implementation facilitates a system interface to automatically create the required instances of *ModelicaBEM*. Based on the class specification, we developed the *Revit2Modelica* prototype to transfer data from Revit into *ModelicaBEM*. The prototype enables a Revit model to contain additional materials and define building topology for *ModelicaBEM*. For example, the prototype implements the *GenerateBuildingTopology()* function to map construction boundary condition types into *ModelicaBEM*. The boundary condition types are calculated based on our predefined rules as follows.

(i) Exterior walls, roofs, and floors, which enclose a room and have nonsharing building components with any other rooms, should be mapped into opaque surfaces.

(ii) Exterior walls enclosing a thermal zone and containing a window(s) should be mapped into opaque surfaces with windows.

```
model Room "A room model for single zone with completely mixed air"
  extends Buildings.Rooms.BaseClasses.ConstructionRecords;
  replaceable package Medium = Medium;
```

Property declaration

```
  parameter Real AFlo;
  parameter Real Height;
  parameter Real Latitude;
  parameter Integer nPorts;
```

Wrapper component declaration

```
  Buildings.Rooms.MixedAir mixedAir(
    redeclare final package Medium = Medium,
    final AFlo=AFlo,
    final hRoo=Height,
    final nConExt=nConExt,
    final datConExt=datConExt,
    final nConExtWin=nConExtWin,
    final datConExtWin=datConExtWin,
    final nConPar=nConPar,
    final nConBou=nConPar,
    final datConBou=datConBou,
    final nSurBou=nSurBou,
    final surBou=surBou,
    nPorts=nPorts,
    energyDynamics=Modelica.Fluid.Types.Dynamics.FixedInitial,
    final lat=Latitude,
    linearizeRadiation=false)
    a;
```

Energy component declaration

```
  Modelica.Blocks.Interfaces.RealInput Room_uSha[1](each min=0, each max=1)
    a;
  Modelica.Blocks.Interfaces.RealInput Room_qGai_flow[3](unit="W/m2")
    a;
  Buildings.BoundaryConditions.WeatherData.Bus Room_weaBus
    a;
  Modelica.Fluid.Vessels.BaseClasses.VesselFluidPorts_b Room_ports[nPorts](
    redeclare each final package Medium = Medium)
    a;
  Modelica.Thermal.HeatTransfer.Interfaces.HeatPort_a Room_heaPorAir
    a;
  Modelica.Thermal.HeatTransfer.Interfaces.HeatPort_a Room_heaPorRad
    a;
  Modelica.Thermal.HeatTransfer.Interfaces.HeatPort_a Room_surf_conBou[nConBou] if haveConBou
    a;
  Modelica.Thermal.HeatTransfer.Interfaces.HeatPort_a Room_surf_surBou[nConBou] if haveSurBou
    a;
```

Connect declaration

```
equation
  connect(Room_uSha, mixedAir.uSha) a;
  connect(Room_qGai_flow, mixedAir.qGai_flow) a;
  connect(Room_weaBus, mixedAir.weaBus) a;
  connect(Room_ports, mixedAir.ports) a;
  connect(Room_surf_surBou, mixedAir.surf_surBou) a;
  connect(Room_surf_conBou, mixedAir.surf_conBou) a;
  connect(Room_heaPorRad, mixedAir.heaPorRad) a;
  connect(Room_heaPorAir, mixedAir.heaPorAir) a;
  a
end Room;
```

Algorithm 2: Implementation of the room class as a wrapper class based on Modelica language specification.

Material instances

```
//Wall material information
  PBIM.BIMPackage.Material WallsMaterial194276(x=0.1, k=0.14, c=900, d=530, R=0.714285714285714);
  PBIM.BIMPackage.Material WallsMaterial205734(x=0.1, k=0.14, c=900, d=530, R=0.714285714285714);
  PBIM.BIMPackage.Material WallsMaterial194278(x=0.1, k=0.14, c=900, d=530, R=0.714285714285714);
```

Wall instances

```
//Wall information
  PBIM.BIMPackage.Wall Walls194276(structure(material={WallsMaterial194276},
    final nLay=1, absIR_a=0.9,absSol_a=0.6),area=11.0700000000014, tilt=1.5707963267949,
    azi=3.14159265358979);
  PBIM.BIMPackage.Wall Walls205734(structure(material={WallsMaterial205734},
    final nLay=1, absIR_a=0.9,absSol_a=0.6),area=16.200000000003, tilt=1.5707963267949,
    azi=1.5707963267949);
  PBIM.BIMPackage.Wall Walls194278(structure(material={WallsMaterial194278},
    final nLay=1, absIR_a=0.9,absSol_a=0.6),area=11.0700000000014, tilt=1.5707963267949, azi=0);
```

Room instances

```
//Room information
  PBIM.BIMPackage.Room Room1(...
    nConExt=5,datConExt(layers={Walls194276.structure,...},
    A={Walls194276.area,...},
    til={Walls194276.tilt,...},azi={Walls194276.azi,...}),
    nConExtWin=0,
    nConBou=1, datConBou(layers={Walls205734.structure}, A={Walls205734.area},
    til={Walls205734.tilt}),
    nConPar=0,nSurBou=0,nPorts=1);
  PBIM.BIMPackage.Room Room2(...
    nConExt=5,datConExt(layers={Walls194278.structure,...},
    A={Walls194278.area,...},
    til={Walls194278.tilt,...},
    azi={Walls194278.azi,...}),
    nConExtWin=0, nConBou=0, nConPar=0,
    nSurBou=1, surBou(A={Walls205734.area},
              absIR={Walls205734.structure.absIR_a}, absSol={Walls205734.structure.absSol_a},
              til={Walls205734.tilt}),
    nPorts=1);
```

Algorithm 3: A code block of the generated *ModelicaBEM* presenting material objects for wall objects, the wall objects, and room objects using the *Revit2Modelica* prototype.

(iii) Shared interior walls between rooms should be defined as opaque surfaces on the location of the interior walls as construction boundaries and surround boundaries between thermal zones.

(iv) Interior walls inside a single room should be mapped into interior partitions in a thermal zone.

In addition, object instances can be generated through the *Revit2Modelica* prototype as shown in Algorithm 3.

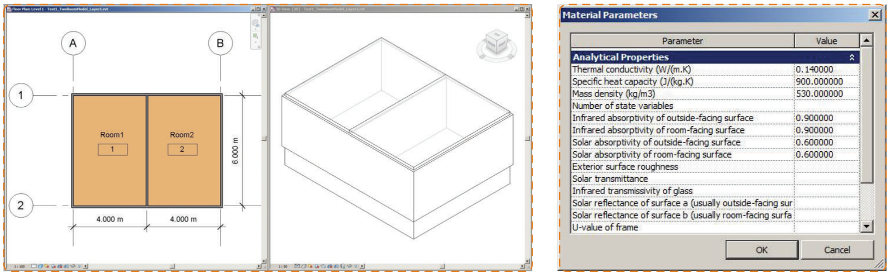
The Exchange MVD enables the object mapping between the two applications based on the object-oriented modeling concept. In addition, the demonstration shows that the MVD follows the Object-Oriented Programming (OOP) approach in the development, which facilitates natural object mapping between Revit and LBNL Modelica Buildings library. Algorithm 3 shows the encapsulation characteristic of the OOP approach; once the required instances are populated from the prototype, the values of them or instances themselves are encapsulated in other instances. As an example of material objects, the material object of a wall is encapsulated as a parameter object in a wall instance to represent the material information.

5. Experiments

To validate the *BIM2BEM* approach, we conducted (1) experiments by applying the class package and *Revit2Modelica* to multizone BIM and (2) simulation result comparisons between two Modelica models: one generated automatically using *Revit2Modelica* and the other manually following the LBNL Modelica Buildings Library samples' approach. For the experiments, three test case models are used. We hypothesized that if our exchange MVD represents all requirements, and if the implementation of the MVD is accurate, the two Modelica models of each test case can produce close or identical simulation results.

5.1. Test Cases.

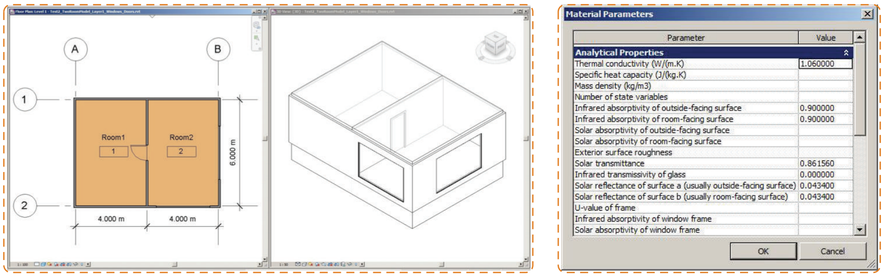
5.1. Test Cases. For the test cases, we created corresponding BIM models using Autodesk Revit Architecture for: a two-room model (Test Case 1), a two-room model having two



Parameter	Value
Analytical Properties	
Thermal conductivity (W/(m.K)	0.140000
Specific heat capacity (J/(kg.K)	900.000000
Mass density (kg/m3)	530.000000
Number of state variables	
Infrared absorptivity of outside-facing surface	0.900000
Infrared absorptivity of room-facing surface	0.900000
Solar absorptivity of outside-facing surface	0.600000
Solar absorptivity of room-facing surface	0.600000
Exterior surface roughness	
Solar transmittance	
Infrared transmissivity of glass	
Solar reflectance of surface a (usually outside-facing sur	
Solar reflectance of surface b (usually room-facing surfa	
U-value of frame	

(a) (b)

Figure 8: A two-thermal-zone Revit model. (a) Floor-plan and isometric views. (b) The custom parameter window for adding additional physical properties.



Parameter	Value
Analytical Properties	
Thermal conductivity (W/(m.K)	1.060000
Specific heat capacity (J/(kg.K)	
Mass density (kg/m3)	
Number of state variables	
Infrared absorptivity of outside-facing surface	0.900000
Infrared absorptivity of room-facing surface	0.900000
Solar absorptivity of outside-facing surface	
Solar absorptivity of room-facing surface	
Exterior surface roughness	
Solar transmittance	0.861560
Infrared transmissivity of glass	0.000000
Solar reflectance of surface a (usually outside-facing surface)	0.043400
Solar reflectance of surface b (usually room-facing surface)	0.043400
U-value of frame	
Infrared absorptivity of window frame	
Solar absorptivity of window frame	

(a) (b)

Figure 9: A two-thermal-zone Revit model with two windows and a door. (a) Floor-plan and isometric views. (b) The custom parameter window for adding additional physical properties for the glazing system.

Table 3: Material specification.

Building components	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)	Mass density (kg/m^3)	Thickness (m)
Walls	0.140	900	530	0.100
Floor	0.140	1200	650	1.028
Roof	0.160	840	950	0.150

windows and an interior door (Test Case 2), and a two-story model having two windows (Test Case 3). Test Case 1 has two thermal zones, six exterior surfaces, and one interior wall. Based on this test case, other models are created to present more building components such as windows, doors, and a new story. The following sections discuss the test cases.

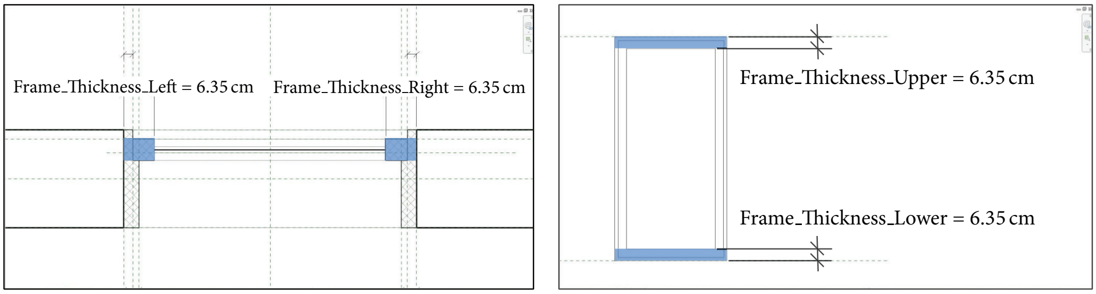
5.1.1. Test Case 1: Creating a Basic Building Model with Two Thermal Zones. Test Case 1 presents a two-thermal-zone model without windows and doors. The building dimensions are 8.0 m $*$ 6.0 m $*$ 2.7 m, respectively, (Figure 8). The basic material information is defined in Table 3.

To add required physical properties in Table 3, we used the *AddPhysicalParameters()* function as shown in Figure 8(b).

The *Revit2Modelica* prototype translates the two-room Revit model into a *ModelicaBEM*. Algorithm 3 shows the generated instances for *ModelicaBEM* from the *Revit2Modelica* prototype. The *GetMaterialInstances()* function in ModelicaBIM class can collect each material instance information used in a BIM model following the Material class of the implemented class package. Wall material objects are instantiated and values for physical properties, which are prepared through the custom parameter window, are assigned to the parameters. Then, the wall objects are instantiated based on the geometry information and the material instances.

The *GenerateBuildingTopology()* function in the *BIMtoModelica* class can retrieve the values of the boundary conditions. As shown in Algorithm 3, the left room has five opaque surfaces (nConExt and datConExt) for three exterior walls, a roof, and a floor, and one opaque surface that is for the interior wall between the thermal zones (nConBou and datConBou); the right room has one opaque surface on the same interior wall between the thermal zones (nSurBou and surBou). The interior wall instance is used in each room (Room instances in Algorithm 3).

5.1.2. Test Case 2: Adding Windows and an Interior Door. We expanded the two-thermal-zone model by installing two windows on the south and east exterior walls, respectively, and a door in the interior wall as shown in Figure 9(a).



(a) (b)

Figure 10: The window family in Revit, (a) a plan view and (b) an elevation view.

Window instance

```
//Window information
PBIM.BIMPackage.Window Windows208788(
  areaWin=5.99981328229248,fFraRatio=0.000991968307418856, structureWin(glass={Glass208788},
  final nLay=1,UFra=3, absIRFra=0.8, absSolFra=0.5,
  haveInteriorShade=false,haveExteriorShade=false));
```

Door instance

```
//Door information
PBIM.BIMPackage.Door Doors210796(redeclare package Medium=MediumA, doorWidth=0.8636,
doorHeight=2.032);
```

Room instance

```
//Room information
PBIM.BIMPackage.Room Room2(...
  nConExt=3 , datConExt(layers={Walls206993.structure,R2.structure,F2.structure},
                        A={Walls206993.area,R2.area,F2.area},
                        til={Walls206993.tilt,R2.tilt,F2.tilt},
                        azi={Walls206993.azi,R2.azi,F2.azi}),
  nConExtWin=2,
  datConExtWin(layers={Walls194278.structure,Walls194279.structure},
                    A={(Walls194278.area*Walls208788.areaWin)/(5.99981328229248),
                      (Walls194279.area*Walls209156.areaWin)/(5.99981328229248),
                    glaSys={Windows208788.structureWin,Windows209156.structureWin},
                    AWin={Windows208788.areaWin,Windows209156.areaWin},
                    fFra={Windows208788.fFraRatio,Windows209156.fFraRatio},
                    til={Walls194278.tilt,Walls194279.tilt},
                    azi={Walls194278.azi,Walls194279.azi}),
  nConBou=0,nConPar=0,
  nSurBou=1, surBou(A={Walls205734.area},
                absIR={Walls205734.structure.absIR_a},
                absSol={Walls205734.structure.absSol_a},
                til={Walls205734.tilt}),nPorts=3);
```

Connect instances

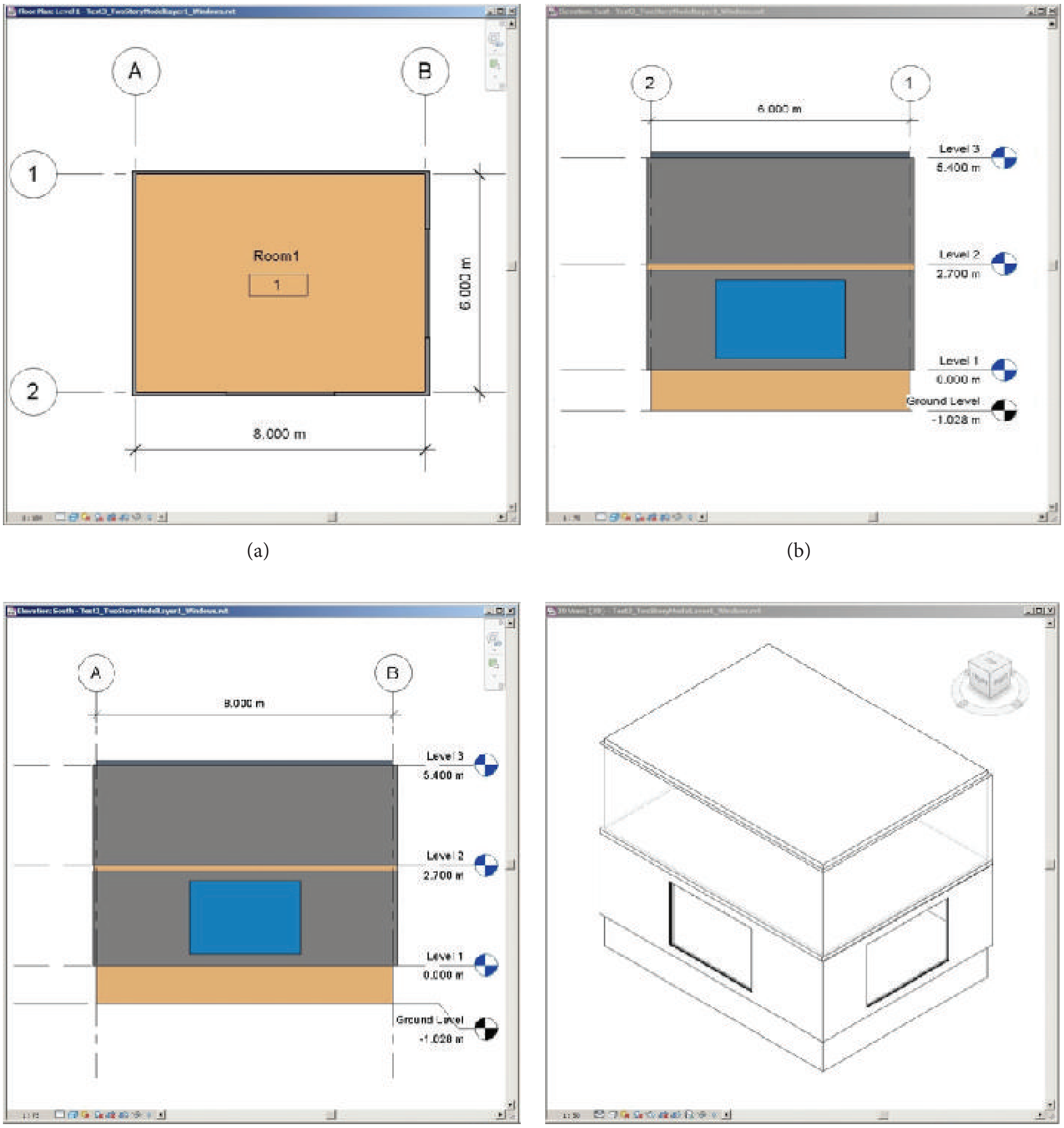
```
//Connect information
connect(Doors210796.port_b1, Room1.Room_ports[2]);
connect(Doors210796.port_a2, Room1.Room_ports[3]);
connect(Doors210796.port_a1, Room2.Room_ports[2]);
connect(Doors210796.port_b2, Room2.Room_ports[3]);
```

Algorithm 4: A code block of the *ModelicaBEM* presenting a window object, a door object, and connect objects of a door generated by the *Revit2Modelica* prototype.

The size of each window is 6 m^2, and the additional physical material information for the glazing system defined in Table 2 is prepared through the custom parameter window (Figure 9(b)).

To prepare the additional thermal information for the glazing system such as the ratio of window frame, we created new parameters in the existing Window family in Revit (Figure 10). The calculated value of the window frame ratio is used as a parameter of a window instance in the *ModelicaBEM* (fFraRatio of the Window instance in Algorithm 4).

By installing two windows in the right room, the room has three opaque surfaces (nConExt and datConExt in



(a) (b)

(c) (d)

Figure 11: A two-story Revit model. (a) Floor-plan view of first level, (b) East-elevation view, (c) South-elevation view, and (d) isometric view.

Room2 of Algorithm 4) and two opaque surfaces with windows (nConExtWin and datConExtWin in Room2 of Algorithm 4).

The line of the Modelica code for a door object is generated through *Revit2Modelica* (the Door instance in Algorithm 4) following the Door class definition in the wrapper classes (Figure 6). By wrapping a Door class, two Modelica *connects* need to be created to calculate bi-directional airflow between two the rooms. Therefore, four Modelica connects are created to link the door and two rooms (Connect instances in Algorithm 4).

5.1.3. Test Case 3: Adding a New Story. To demonstrate a zoning case for vertical stacking of rooms, we created a two-story Revit model as shown in Figure 11. The building has one room on each floor and a 6 m^2 window on each of the south wall and the west wall at the first floor.

Based on the BIM of the building, *Revit2Modelica* creates *ModelicaBEM* that enables heat transfer to be simulated between two stories. The mechanism of the heat transfer is similar to Test Case 1. The major difference is that the floor object, instead of the interior wall, connects two thermal zones.

The roof instance in the lower level and the floor instance in the upper level are modeled in the *ModelicaBEM* as opaque surfaces (the Floor instance and the Roof instance in Algorithm 5). Then, a Modelica *connect* is created to link the opaque surfaces for conduction heat transfer calculation.

In terms of boundary conditions, the right room of Test Case 1 and the upper room in Test Case 3 have the same

Floor instance

```
//Floor information of upper level
  PBIM.BIMPackage.Floor F2(structure(material={Floors206671},final nLay=1),
                     area=48.0000000000001,tilt=3.14159265358979,azi=3.14159265358979);
```

Roof instance

```
//Roof information of lower level
  PBIM.BIMPackage.Roof F2206671(structure(material={Floors206671},final nLay=1),
                           area=48.0000000000001,tilt=0,azi=0);
```

Room instance

```
//Room information of upper level
  PBIM.BIMPackage.Roof Room2(...
    nConExt=5 ,datConExt(layers={Walls206727.structure,...,R1.structure},
                           A={Walls206727.area,...,R1.area},
                         til={Walls206727.tilt,...,R1.tilt},
                         azi={Walls206727.azi,...,R1.azi}),
    nConExtWin=0, nConBou=0, nConPar=0,
    nSurBou=1 , surBou(A={F2.area},
                  absIR={F2.structure.absIR_a},
                  absSol={F2.structure.absSol_a},
                    til={F2.tilt}),nPorts=1);
```

Algorithm 5: Generated *ModelicaBEM* code block of the two-story building model presenting the floor instance, the roof instance, and the room instance at the upper level.

number of opaque surfaces (nConExt and datConExt) and another opaque surface between two thermal zones in each case (nSurBou and surBou). In Test Case 3, the five opaque surfaces in the upper room consist of four walls and a roof, and the one opaque surface between the lower room and the upper room is the floor object (Room instance in Algorithm 5).

As shown in Algorithms 3, 4 and 5, the generated three *ModelicaBEM* of the three test cases demonstrate the use of the *Revit2Modelica* prototype. To validate the method and the prototype, we conducted simulation result comparisons explained blow.

5.2. Simulation Result Comparisons. We utilized Dymola as a Modelica development environment and LBNL Modelica Buildings library version 1.3 to perform thermal simulation with the *ModelicaBEM*. As Modelica Buildings requires designation of time intervals and tolerances, the simulation settings include time interval of 3600 seconds for a one-year period and a tolerance of 10^{-6}.

We applied the consistent model conditions for all the building models as follows.

(i) The floor is above the ground level.
(ii) Each room is a single thermal zone.
(iii) The building location is Chicago, Illinois, USA.
(iv) The building has no shading devices and no internal heat gains from equipment and occupants.
(v) The building has no HVAC systems.
(vi) The windows and the door are closed.

The simulation results of each test case model agree with the results of each of the corresponding model created manually using the LBNL Modelica Buildings library sample structure by us, in terms of annual indoor air temperature and heat flow.

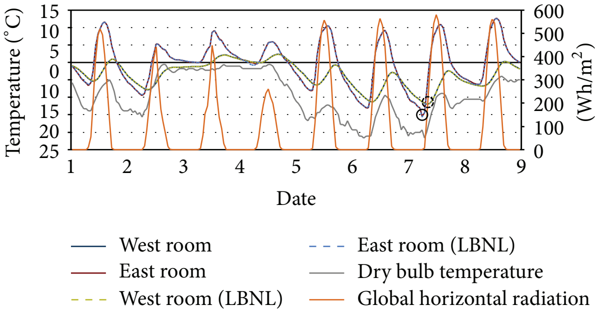


Figure 12: Temperature comparison of Test Case 2 for February 1st to 9th. Solid (6AM, February 7th) and broken (8AM, February 7th) circles point out the lowest temperature in the East and West Rooms, respectively, for the two models. The temperature curves overlap between the two models.

The indoor air temperatures of each Modelica model in the test cases are almost identical with those of LBNL's models. For example in Test Case 2, as shown in Table 4, the highest temperatures are obtained at 12PM on August 21th in East Rooms in both models, and in Test Case 3, the lowest temperatures are obtained at 8AM on January 8thin the Upper Rooms in both models.

Figures 12, 13, and 14 show the results in Test Case 2: the indoor air temperatures of *ModelicaBEM* and LBNL's model, global horizontal radiation, and a dry bulb outdoor temperatures during different time periods and for different rooms from February 1st to 9th, from July 18th to 26th, and from August 14th to 22nd respectively.

Table 4: Annual peak temperatures of the test cases.

Cases	Room name	Highest temperature (°C)/Date-Time	Lowest temperature (°C)/Date-Time
1	East	ModelicaBEM: 34.63°C/July 19th-6PM	ModelicaBEM: –15.479°C/February 7th-8AM
		LBNL model: 34.66°C/July 19th-6PM	LBNL model: –15.471°C/February 7th-8AM
	West	ModelicaBEM: 35.222°C/July 18th-7PM	ModelicaBEM: –15.655°C/February 7th-9AM
		LBNL model: 35.237°C/July 18th-7PM	LBNL model: –15.658°C/February 7th-9AM
2	East	ModelicaBEM: 42.827°C/August 21st-12PM	ModelicaBEM: –15.369°C/February 7th-6AM
		LBNL model: 42.968°C/August 21st-12PM	LBNL model: –15.669°C/February 7th-6AM
	West	ModelicaBEM: 35.485°C/July 18th-6PM	ModelicaBEM: –11.967°C/February 7th-8AM
		LBNL model: 35.413°C/July 18th-6PM	LBNL model: –11.955°C/February 7th-8AM
3	Upper	ModelicaBEM: 38.085°C/July 18th-6PM	ModelicaBEM: –21.289°C/January 8th-8AM
		LBNL model: 38.035°C/July 18th-6PM	LBNL model: –21.283°C/January 8th-8AM
	Lower	ModelicaBEM: 40.144°C/July 18th-2PM	ModelicaBEM: –10.348°C/February 7th-6AM
		LBNL model: 40.047°C/July 18th-2PM	LBNL model: –10.029°C/February 7th-6AM

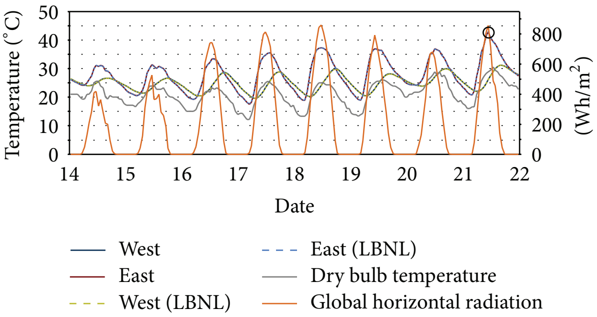


Figure 13: Temperature comparison of Test Case 2 for August 14th to 22nd. Solid circle (12PM, August 21st) points out the highest temperatures of the East Room. The temperature curves overlap between the two models.

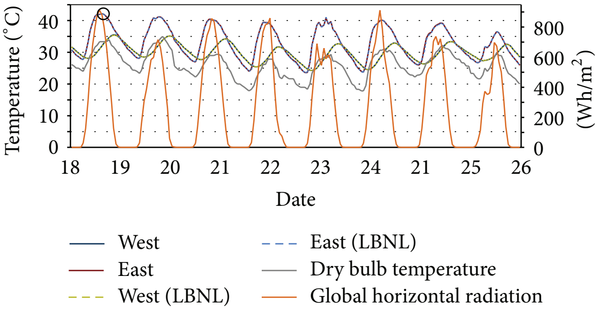


Figure 14: Temperature comparison of Test Case 2 for July 18th to 26th. Solid circle (6PM, July 18th) presents the highest temperatures of the West Room. The temperature curves overlap between the two models.

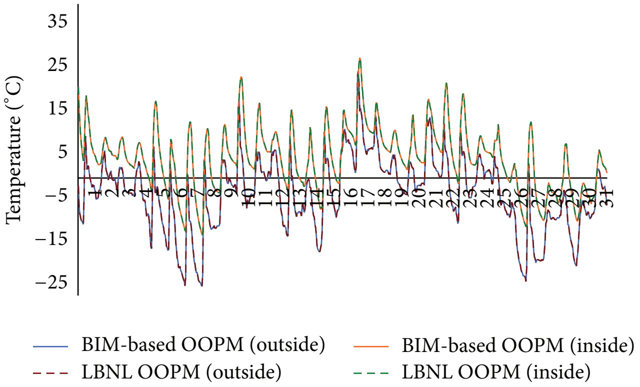


Figure 15: Temperature comparison between the two models for the east wall in Test Case 2 during January.

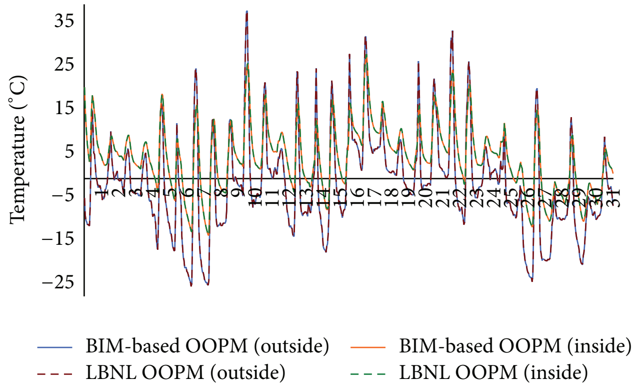


Figure 16: Temperature comparison between the two models for the south wall in Test Case 2 during January.

We also conducted a validation case study for component level analysis. We examined the temperatures from outside surfaces and temperatures of the inside surfaces of the east and south walls each having a window in Test Case 2. As shown in Figures 15 and 16, the temperature graphs of *ModelicaBEM* almost overlap those of LBNL's model.

Overall, the BIM-based *ModelicaBEM* models created by our prototype produce very similar simulation results as LBNL's models. This is expected because the same thermal simulation algorithm provided by LBNL Modelica Buildings library is applied to all the energy models.

The modeling method (automatic versus manual) and model structures (one is BIM-based and the other is not) are the major differences between *ModelicaBEM* and the LBNL's models. The simulation results will have inconsistency during the comparison studies if the model translations were not done correctly by *Revit2Modelica*. *Revit2Modelica* generates the energy models that are reasonably more comprehensive to reflect the actual building configuration. In the example of Test Case 3, the LBNL's Modelica model represents the floor object as a roof object for the lower thermal zone and a floor object for the upper thermal zone. Based on the understanding of energy semantics, for example, boundary condition, the shared floor object is modeled into thermal zones manually. However, our approach automatically splits the floor object as two components to represent the actual building configuration: one is for a floor object in the upper room and the other is for a roof object in the lower room.

In terms of the model structure, *Revit2Modelica* generated energy models present to the user architectural semantics such as rooms, instead of energy engineering-based semantics such as MixedAir. In addition, the two structures can have a difference regarding the order of building enclosure elements used as arguments in thermal calculation functions, causing the slightly different simulation results. The result differences due to this argument order difference can be reduced through decreasing the model tolerance value in Dymola.

6. Conclusions and Future Work

This paper presents a translation method for integrating BIM and OOPM (Modelica) for building energy simulation. Our *BIM2BEM* development enables interdisciplinary data exchange between architectural design and building energy simulation. *BIM2BEM* can leverage the consistent use of the architect's data (such as the building geometry, materials, and even parametric objects) in building energy simulation without recreating them in energy models manually. Reuse of the data from BIM can significantly reduce the effort required for the definition of input data in BEM. The process presented in this paper has the potential to eliminate error-prone manual processes.

Our data modeling approach facilitates the development of a system interface for automatic translation from BIM to BEM with high efficiency and accuracy. While the file-based translation through standard schema such as IFC and gbXML can often facilitate the translation between different BIM tools and different simulation applications, implementing the complex schemas of IFC demands enormous amount of time and efforts [38]. The developed prototype based on the Exchange MVD enables more seamless design-simulation integration while the BIM tools (such as Revit) can preserve the parametric modeling capability in the process. The current version of the MVD is applicable for Revit; however, the MVD and the system interface can be developed to support other BIM tools such as ArchiCAD, AECOsim Building Designer V8i, and Allplan. Nevertheless, the use of IFC can better bridge between multiple BIM authoring tools and diverse simulation tools.

The process for assigning additional physical parameters is semiautomatic: users are expected to assign the values of the parameters manually, but the parameters are created in BIM automatically. In the future development, this process can be fully automated by linking the material parameters to existing material database in order to retrieve the parameter values. In the present system, after a complete BIM model is created with all required information, the translation process is automatic.

As an application, the developed system interface supports object-based thermal performance results to be displayed using data graphs in BIM so that building designers can inspect the results directly in BIM [34].

A major advantage of our approach is that Modelica is supported by a growing community of researchers who are developing various physics-based modules for simulation. Our approach is generalizable to integration of BIM to other physics-based simulations. Currently, our *BIM2BEM* approach is focused on thermal simulation. In future work, we will expand *BIM2BEM* to cover more simulation domains including daylight and photovoltaic. Moreover, we will apply our prototype to test more building types including complex buildings to enhance the *BIM2BEM* translation method and collect measured data from real-world project to validate the *BIM2BEM* approach. We will also examine more general boundary condition generating methods, for example, [6], and apply them into the system interface of *BIM2BEM*.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

Developing Mobile BIM/2D Barcode-Based Automated Facility Management System

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Facility management (FM) has become an important topic in research on the operation and maintenance phase. Managing the work of FM effectively is extremely difficult owing to the variety of environments. One of the difficulties is the performance of two-dimensional (2D) graphics when depicting facilities. Building information modeling (BIM) uses precise geometry and relevant data to support the facilities depicted in three-dimensional (3D) object-oriented computer-aided design (CAD). This paper proposes a new and practical methodology with application to FM that uses an integrated 2D barcode and the BIM approach. Using 2D barcode and BIM technologies, this study proposes a mobile automated BIM-based facility management (BIMFM) system for FM staff in the operation and maintenance phase. The mobile automated BIMFM system is then applied in a selected case study of a commercial building project in Taiwan to verify the proposed methodology and demonstrate its effectiveness in FM practice. The combined results demonstrate that a BIMFM-like system can be an effective mobile automated FM tool. The advantage of the mobile automated BIMFM system lies not only in improving FM work efficiency for the FM staff but also in facilitating FM updates and transfers in the BIM environment.

1. Introduction

Facility management (FM) during the operation and maintenance phase of a facility's lifecycle has become an important topic in research and academic studies. Managing the inspection and maintenance information of equipment and facilities contributes to successful FM. Managing the work of FM effectively during the operation and maintenance phase can be extremely difficult owing to the various types of equipment and facilities. Furthermore, it is inconvenient for FM staff to maintain those facilities by relying on paper-based documents. Unlike the manufacturing industry, information technology is limited in its use and its application in construction [1], with human labor conducting most of the management work, which is inefficient and sometimes error-prone [2].

Building information modeling (BIM) is a computable representation of all of a building's physical and functional characteristics and related lifecycle information and serves as a repository of information for building owners and operators that is used and maintained throughout the lifecycle of a building [3]. BIM is an emerging visual communication tool in the architecture, engineering, and construction (AEC) industry. Recently, various BIM applications have been applied during design and construction phases. However, without a maintenance stage application, BIM cannot fulfill the "lifecycle" mission. Although many projects have been implemented for FM with the use of BIM technology, problems and challenges remain in applied BIM technology that need to be solved and improved in practice.

In FM, the staff usually refers to information such as specifications, checklists, maintenance reports, and maintenance records. As FM staff must record inspection and maintenance results in hard copies, there can consequently be significant gaps in data capture and entry. Such means of communicating information between the facility location and the management office are ineffective and inconvenient. According to the survey findings regarding maintenance work on a commercial building in Taiwan [4], the primary problems regarding data capture and sharing during the FM

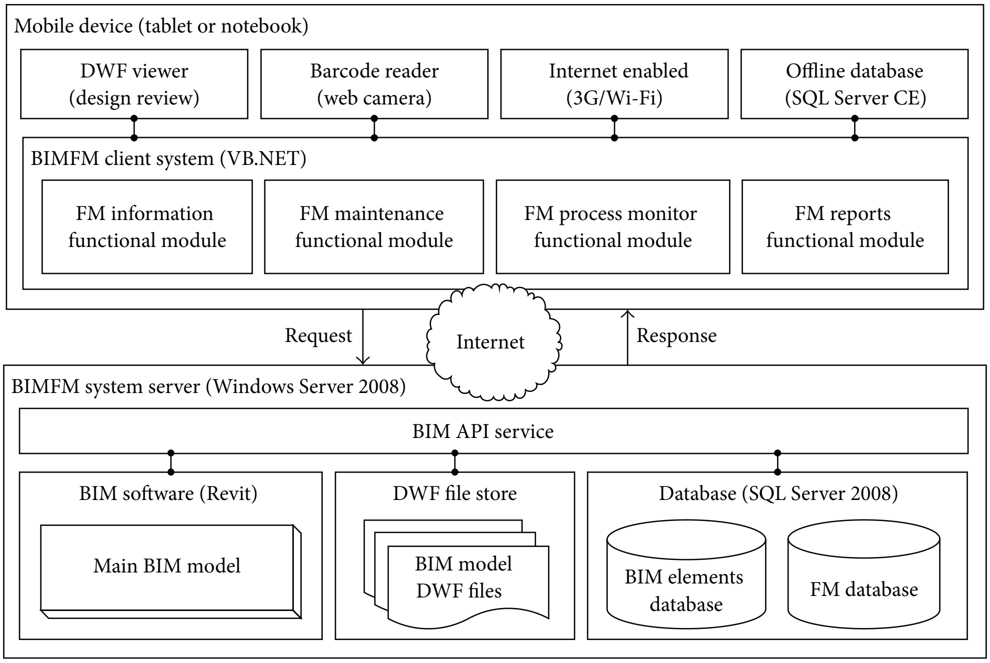


Figure 1: Overview of the BIMFM system framework.

process are as follows: (1) the efficiency and quality are low, especially through document-based media; (2) it is not easy to refer to the relevant detailed information on facilities; (3) there are data reentry problems; and (4) the use of desktops for operating the BIM models cannot be effectively extended to maintenance management services at the facility location. However, few suitable platforms exist to assist FM staff in using an integrated FM information system from the BIM models and in sharing maintenance information directly at the facility's location.

The performance of FM can be enhanced by using Internet technology for information-sharing and communication. In this study, the work of FM includes inspection and maintenance work. By integrating automatic identification technologies (such as two-dimensional (2D) barcode systems), the effectiveness of FM work is enhanced and improved (see Figure 1). In order to enhance the effectiveness of FM work on commercial buildings, this study presents a novel system called the mobile automated BIM-based facility management (BIMFM) system for the acquisition and tracking of maintenance information and provides an information-sharing platform for FM staff that may be accessed with the use of a webcam-enabled notebook or tablet. Integrating BIM and 2D barcode technologies, information, and data entry mechanisms can help to improve the effectiveness and convenience of the information flow in the FM process. The primary objectives of this study include (1) applying BIM and 2D barcode technologies to increase the efficiency of FM data and information collection, (2) directly accessing 2D barcode technologies to link detailed information to the BIM models of facilities, (3) developing a mobile BIM/2D barcode-based system to assist directly the BIM-based maintenance management work at facility locations, and (4) exploring the limitations of the system, addressing problems, and providing suggestions based on the implementation of the case study. The mobile automated BIMFM system is applied to a commercial building in Taiwan to verify our proposed methodology and demonstrate the effectiveness of the FM process in construction. There are two hypotheses in this study: the first is that all BIM models are developed during the construction phase and made ready for FM; the second is that all BIM models must be updated and corrected constantly.

2. Related Research Studies

A substantial amount of research has shown the potential of one-dimensional barcode applications in various areas of the construction industry, such as data entry efficiency, labor management, productivity improvement, cost savings, construction equipment and materials tracking, and electronic document management [5–9]. McCullouch and Luepraser [10], for example, illustrated how 2D barcode technology could be applied in the construction industry. Various other research works on the application of barcode models have focused on the integration of other technologies. Navon and Berkovich [11], for example, used barcode and radio frequency identification (RFID) technologies for automated data collection to assist with materials management and control. Shehab and Moselhi [12] illustrated the use of barcode technology to develop an automated system for retrieving engineering deliverables such as drawings, reports, and specifications. Saeed et al. [13] integrated a global positioning system (GPS) with RFID and 2D barcode technologies to provide a solution for pedestrian users that allowed them to access information about buildings and other artifacts.

BIM is changing the traditional construction practices in a broader sense in terms of people, process, working culture, communication, business models, and so forth [14]. Many core benefits, barriers, frameworks, and recommendations for BIM usage are cited in previous work on supporting decisions and improving processes throughout the lifecycle of a project [3, 15–24]. A substantial amount of previous research has examined BIM issues in the operation phase of construction. The Sydney Opera House adopted BIM technology as a means of support for their integrated facility management [25]. Motamedi et al. [26] utilized BIM visualization capabilities to provide FM technicians with visualization that allowed them to utilize their cognitive and perceptual reasoning for problem solving. Becerik-Gerber et al. [27] assessed the status of BIM implementations in FM, the potential applications, and the level of interest in the utilization of BIM by conducting online surveys and face-to-face interviews. Wang et al. [28] not only developed a framework through which one could consider FM in the design stage through BIM but also explored how BIM would beneficially support FM in the design phase. Lin et al. [29] processed different kinds of building components and their corresponding properties to obtain rich semantic information that could enhance applications of path planning in FM. Costin et al. [30] utilized RFID technology for real-time visualization and location tracking in a BIM model. Gheisari et al. [31] explored the ways through which one could integrate BIM with mobile augmented reality (MAR) and make the data accessible through handheld mobile devices in order to enhance current facility management practices.

The BIM approach, which is used to retain facility information in a digital format, facilitates easy updates of FM information in a BIM environment. Although there are many practical applications for using BIM in the maintenance management stage, there are challenges as well. One of the challenges involves the accessibility of the BIM models for FM staff: it usually takes time to refer to and link the corresponding FM element in the BIM model during the maintenance and inspection process [32]. To assist FM staff in obtaining the corresponding BIM model for facilities maintenance management in an automatic and effective manner, this study develops a proposed system that integrates 2D barcode technology to connect automatically to the BIM models. This study then manages facilities by using the 2D barcode technology that is integrated with the BIM approach. By using 2D barcode technology, users can link to the corresponding BIM model of a facility in a quick, automatic, and effective way and access basic information and maintenance problems, while managing FM information during the operation and maintenance phase. Next, the proposed BIMFM system is applied to a case study of a commercial building project in Taiwan to verify its efficacy and demonstrate its FM effectiveness in a BIM-based environment. Finally, the limitations, problems, and suggestions are discussed based on the implementation of the case studies in this study.

3. Key Technologies

3.1. BIM Technology. BIM is one of the most promising recent developments in the AEC industry [33]. It was developed nearly ten years ago with the aim of providing an environment from which any related information on three-dimensional (3D) entity models could be retrieved during the project lifecycle [14, 34]. BIM is considered essential in AEC for the management, sharing, and exchange of information among project stakeholders such as architects, engineers, contractors, owners, and subcontractors [35], although its technologies are being adopted more slowly in the AEC industry than 2D computer-aided design (CAD) [36, 37]. By enabling visualization of the details of the prospective work, BIM assists construction planners in making crucial decisions [38]. BIM is a new technology in the field of CAD, which contains not only geometric data but also a great amount of engineering data throughout the lifecycle of a building [39]. As a digital tool, BIM supports the continual updating and sharing of project design information [30]. A BIM system enables users to integrate and reuse building information and domain knowledge throughout the lifecycle of a building [40].

There are many BIM commerce tools for creating BIM models (e.g., Autodesk Revit, Trimble Tekla, and the Graphisoft ArchiCAD software). Most of these commerce tools provide software development kits (SDK) for programming purposes. For this study, Autodesk Revit is selected as the main BIM tool because it provides more SDK support than other commerce tools. Furthermore, the use of Autodesk Revit allows the easy export of all of the information regarding a BIM model to a database through open database connectivity (ODBC).

3.2. 2D Barcode Technology. Another technology explored as a means of providing accurate and reliable real-time inspection information is the 2D barcode system. The 2D barcode system also has the ability to deliver information on location, including text, audio, and video. Barcode technology was invented in 1950 and it developed rapidly during the subsequent years. With the advantages of higher capacity, lower cost, increased security, traceability, anticorruptibility, and mistake-correcting functionality, the 2D barcode has been widely applied since 1990 [9]. The major characteristics of the 2D barcode are its capacity to represent data content and its arrangement of a specific geometric diagram in a relatively small matrix area that can record significant quantities of data. The 2D Stacked Code and the 2D Matrix Code are the two typical types of barcode classified by their design principle. The 2D Stacked Code was developed based on the one-dimensional barcode. It is composed by thinning down the one-dimensional barcode and stacking it in layers to create multirow symbols. Representative types of the Stacked Code include Code 16 K, Code 49, and Portable Data File 417 (PDF417). The 2D Matrix Code was composed by the distribution of black-white picture elements (square, dot, or other types) in a square area in relative matrix position.

Representative types of Matrix Codes include code one, maxi code, quick response (QR) code, and data matrix.

Although many types of 2D barcodes exist, as shown above, the QR code is the most popular type of 2D barcode used in Taiwan. The advantages of the QR code are as follows:

(1) high capacity of data content: the QR code can record thousands of characters or numbers, since its capacity is ten times greater than that of the one-dimensional barcode;

(2) various data types: the data types stored in the 2D barcode include image, sound, words, and fingerprints, with the capacity for multilanguage expression;

(3) ease of production: the scale and shape of the QR code are changeable and are easily made by software and a printer, at a low cost;

(4) convenience: the QR code can easily be identified by a mobile phone or a mobile device and is readable in any direction (http://www.qrcode.com/en/about/).

Although RFID technology is suitable for long-distance reading in FM work, the cost of RFID readers and tags is a major problem when many readers and tags are needed. Furthermore, tablets have free software for reading the QR code. Therefore, the QR code is selected and utilized in this study because QR code labels are cheaper than RFID tags.

4. System Schematic Design

The 2D barcode has been widely applied in Taiwan. With the advancement of mobile technology, many mobile phones are equipped with cameras, which have the capability to scan 2D barcodes. When a barcode reader program is installed, the user can quickly access product descriptions, web addresses, or e-mail addresses by scanning the barcode. For example, a mobile phone with the Google Android system can read one- or two-dimensional barcodes such as the international article number (EAN), the international standard book number (ISBN), or the QR code after installing the Zxing barcode scanner software. Tablets equipped with cameras also enable the application of 2D barcode scanning to facilitate maintenance management of building facilities. The 2D barcode can be easily identified by mobile devices and record thousands of characters or numbers, since its capacity is ten times greater than the one-dimensional barcode. Furthermore, the 2D barcode's ability to decode mistakes is much higher than that of the one-dimensional barcode [9]. In this study, the main reason for using the 2D barcode is that the brief information and the uniform resource locator (URL) for directly linking the BIM models can be stored within the 2D barcode, unlike the one-dimensional barcode. It is an easy and effective way to link to the BIM models. In this study, we do not adopt an RFID solution because the use of RFID requires RFID tags and an additional RFID reader hardware. The purchasing cost of the RFID tags and the additional RFID reader hardware would be higher than the cost of the 2D barcodes used in this study. Furthermore, 2D barcode labels can be printed without the use of a specialized printer and can be scanned and read by webcam-enabled tablets. Based on the considerations of cost and effectiveness, the 2D barcode is a better choice for implementation. Therefore, this study integrates BIM and 2D barcode technologies to enhance FM work and provide detailed FM information communication. An integrated client/server platform can link all of the information on building facilities to improve the effectiveness of the FM process.

The application of BIM/2D barcode technology in the management of facilities both inside and outside of the buildings focuses on its rapid identification and supports FM staff in handling FM via the 3D BIM models. By scanning the 2D barcode label sticker on a facility, FM staff can obtain the corresponding BIM model of the facility and directly access FM information about the facility, such as instruction manuals, photos, videos of operations, maintenance history, and manufacturer information. Furthermore, a 3D BIM model improves upon the traditional 2D drawings that had difficulty illustrating the vertical location or position of facilities.

The BIMFM system consists of subsystems for BIM, 2D barcodes, mobile devices, and a hub center. The BIM, 2D barcodes, and mobile devices subsystems are located on the client side, while the hub center subsystem is on the server side. Each subsystem is briefly described below.

4.1. BIM Subsystem of the BIMFM System. In this study, BIM is used as an information model in the BIMFM system and applied to capture and store information about the facility, including basic descriptions, parameter-related information, maintenance records, and interface reports. Autodesk Revit software was used to create the BIM model files. Autodesk Design Review was used to read the BIM models of facilities. Information integration with the 3D BIM models was achieved using the Autodesk Revit application programming interface (API) and the Microsoft Visual Basic.Net (VB.Net) programming language. The BIMFM system was developed by integrating the 3D BIM models of facilities and maintenance-related information using Revit API programming. ODBC was utilized to integrate the acquired data from different software programs and all maintenance information, such that BIM files, can be exported to an ODBC database for connection with the BIMFM system.

4.2. 2D Barcode Subsystem of the BIMFM System. Most people in Taiwan have personal smart phones and tablets and can easily access 2D barcode information. The case study uses the QR code as the 2D barcode system since the QR code reader software is popular in Taiwan and provides the most suitable functionality for facilities maintenance management. The QR code label has a high fault tolerance and its anticorruption capability contributes to longer usage and better identification. One of the major advantages of using the 2D barcode is that no extra cost is required to buy software, since a great number of 2D barcode software applications for tablets are free. Furthermore, all types of 2D barcode labels can be created using a personal computer (PC) printer.

4.3. Mobile Devices Subsystem of the BIMFM System. Two mobile devices are used in the BIMFM system. A Samsung Series 7 tablet is used as the webcam-enabled tablet hardware. The Samsung Galaxy Tab runs on Windows 8. All data in the tablet module are transmitted to the server directly through the Internet. An HP Pavilion notebook is used as the webcam-enabled notebook hardware. The HP Pavilion notebook runs on the Windows 7 operating system. All data in the tablet and the notebook are transmitted to the server directly through the Internet via Wi-Fi or third generation (3G).

4.4. Hub Center Subsystem of the BIMFM System. The hub center is an information center in the BIMFM system that enables all participants to log on to a hub center and immediately obtain information required for FM. Users can access different information and services via a single front-end access point on the Internet. For example, FM staff can log on to the hub center and securely access the latest FM schedule information. FM managers can check maintenance status, results, and various other inspection-related data. All facilities-related information acquired within the hub center subsystem is recorded in a centralized system database. FM staff can access the required information via the hub center subsystem based on their access privileges.

The amount of maintenance information stored will increase over time if all FM information is recorded in the BIM model. Because BIM models cover a wealth of building information, system storage space should be reserved for crucial information, such as spatial information, facility ID and name of the facility, facility location, and other critical information. In order to keep the system performance at an acceptable level, the information derived by other applications should be stored in an external location. Therefore, two databases are incorporated into the design of the BIMFM system: the BIM elements database and the FM database. The BIM elements database stores only basic information (such as the position, ID, and name of the facility and key parameter information of components). Related maintenance data and information are stored in the FM database.

The accuracy of the BIM model will directly affect FM operations in the BIMFM system. To prevent too many users from simultaneously using the BIM models and, in turn, affecting their accuracy, the BIM engineer can update the information from the BIM elements database directly in the BIMFM system. The latest information in the BIM elements database automatically resyncs when content changes. In this framework, all building facility information from BIM can be saved and updated in the BIM elements database without directly accessing the BIM models.

FM operations do not require all building information; they only require information about necessary maintenance, although the BIM model may cover the whole building. Therefore, during the pre-FM process, the BIM engineer is responsible for determining whether to create the DWF (design web format) file of the BIM model in advance and save it as a source for decomposed BIM models based on the requirements of the FM operations. Not only can the DWF format retain building information, but also its file size is smaller than the general BIM model file. The BIMFM system can be improved with the use of the DWF file for the 3D BIM illustrations, and the system's performance is enhanced for users by reviewing the 3D BIM models. Furthermore, the BIM elements database in the server can store accurate information on the BIM models.

In the BIMFM system, the following three major roles are involved in FM: a BIM engineer, an FM manager, and FM staff. To ensure that the FM operation does not affect the maintenance operation of the BIM model, this study utilizes client-server system architecture. In the BIMFM system, the BIM elements database stores all of the information on the BIM models on the server side. In addition, only BIM engineers are allowed to access and edit the BIM models and export data to the BIM elements database using the BIM software directly on the server side. On the client side, the FM manager and FM staff refer to facility information through the BIM elements database and edit FM information through the FM database in the BIMFM system.

The BIMFM system server supports four distinct layers, each with its own responsibilities: management, data access, application, and presentation. The following section describes these four distinct layers in the BIMFM system.

The management layer provides BIM engineers with the tools to edit and manage BIM models using the BIM software. BIM engineers can access and edit the BIM models saved in the server through the Internet. With the development of the BIM tool APIs, the management layer can not only export data from the BIM models to the BIM elements database but also import data from the BIM elements database to the BIM models. Furthermore, facilities maintenance information can also be recorded in the BIM elements database in the management layer.

The database layer in the BIMFM system consists of two databases: the FM database and the BIM elements database. The FM database stores all facilities maintenance records, while the BIM elements database stores complete facility information, including facility number, name, and type, in the BIM models. The FM database records detailed maintenance information in accordance with the facility ID. The primary key establishes a relationship between the facility ID and the main index. Therefore, information can be used for data association for data mapping to retrieve complete facilities maintenance information based on the facility ID between the two databases.

The application layer defines various applications for the major system and API modules. These applications offer indexing, BIM model data updates and transfers, facility status visualization, and report generation functions. The application layer integrates and uses the BIM software to open the BIM models using developed API modules. Finally, the application layer can automatically acquire data and analyze the BIM models based on a request and then send the results back to the client side.

The presentation layer is the main implementation platform of the BIMFM system. During the FM process, the FM manager and FM staff can use a tablet (client side) and the utilities in the BIMFM system for the FM operation.

The presentation layer is integrated with a QR code device, automatically displays the location information of the BIM model, records maintenance information, illustrates the different conditions and status of FM, queries the history, and exports reports on FM results.

5. System Development

The BIMFM system server is based on the Microsoft Windows Server 2008 operating system with an SQL Server 2008 R2 as the database. The BIMFM system is developed using VB.NET programming, which is easily incorporated with ADO.NET to transact FM and BIM information with an SQL Server database. The BIMFM system consists of three different user areas, FM staff, FM manager, and BIM engineer areas. Access to the BIMFM system is password-controlled.

5.1. System Functionality Description. This section describes the implementation of each major functionality module in the BIMFM system (see Figure 2).

5.1.1. FM Information Functional Module. The functional module provides FM staff with detailed FM information on facilities by reviewing 3D BIM models. This module enables all FM staff to refer to related FM information and historical maintenance records for the selected facility quickly and easily in the 3D BIM-based environment. This module allows FM staff to refer to basic information and specifications associated with 3D BIM models during the FM process. This module also has a search function that enables the information to be found and retrieved easily.

5.1.2. FM Maintenance Functional Module. FM staff can download up-to-date maintenance records through the 3D BIM models and enter facility maintenance results directly into the 3D BIM models. Additionally, the module can automatically produce the corresponding maintenance forms through the 3D BIM models. Tablets display the checklist for every facility maintenance task. FM staff can record maintenance information such as dates, conditions, inspection results, descriptions of problems that have arisen during maintenance, and recommendations. Furthermore, FM staff can also check tasks that do not pass the inspection and select relevant tasks from lists in the 3D BIM models. One of the benefits of the module is that maintenance results and records can be transferred between a tablet and the BIMFM system by real-time synchronization, eliminating the need to enter the same data more than once.

5.1.3. FM Process Monitor Functional Module. This functional module is designed to enable FM managers to monitor the FM process. The process monitor module provides an easily accessed and portable environment where FM staff can trace and record all maintenance information and status through the visualized and colorized BIM model.

5.1.4. FM Reports Functional Module. Users can easily access the FM reports functional module to identify needs and analyze FM results information. Authorized records for interfaces can be extracted and summarized for the final FM result-related reports. Furthermore, all FM reports can be extracted using commercially available software such as Microsoft Excel.

5.2. System API Modules Description. In order to integrate the system with the BIM models, the following API modules are developed in the BIMFM system.

5.2.1. The BIM Model Data Synchronization API Module. The main function of this module is to automatically synchronize the latest information on the BIM models with the BIM elements database. Although the BIM software provides the open database connectivity (ODBC) database export function, there are still many required data elements for FM that cannot be exported through this function, such as self-defined parameters information in the BIM elements modules. That functionality is provided by the API. All required information in the BIM models is automatically synchronized to the BIM elements database based on required information for FM by the API development. The module will retain the existing data and update the changed data synchronization if the exported information already exists in the BIM elements database.

5.2.2. Facility Barcode Generation and Reader API Module. This module generates a QR code label automatically and links to the related facility BIM module or BIM element module. Because there are typically thousands of facilities for FM, the FM staff usually requires significant time and effort to make QR code labels for FM purposes. To address this problem, the module can generate the QR code label to obtain basic required information (such as device number and purchase date) and linkage to related 3D BIM modules. By scanning the QR code, users can link and check the related BIM modules directly without spending too much time searching for them. Furthermore, a QR code can be generated and accessed quickly to find available BIM models in the room corresponding to the facility location.

5.2.3. Automated Focus on Facility Elements API Module. This module allows users to access the related BIM models by scanning a QR code label attached to the surface of the facility. When the user scans the QR code label, this module will automatically identify the facility or facility location based on the corresponding floor to open the corresponding BIM models file (in DWF format). If the facility is positioned too high up to scan its QR code label, the user may scan the QR code label attached to the entrance of the room and directly select and access the corresponding BIM models in the room.

5.2.4. BIM Model Data Update API Module. This module provides the functionality for updating facility information from the FM database to the main BIM model automatically. The DWF format of BIM models in the BIMFM system allows users to view and access BIM models without changing any information in the BIM models. When FM-related information changes and requires feedback to the BIM model (e.g.,

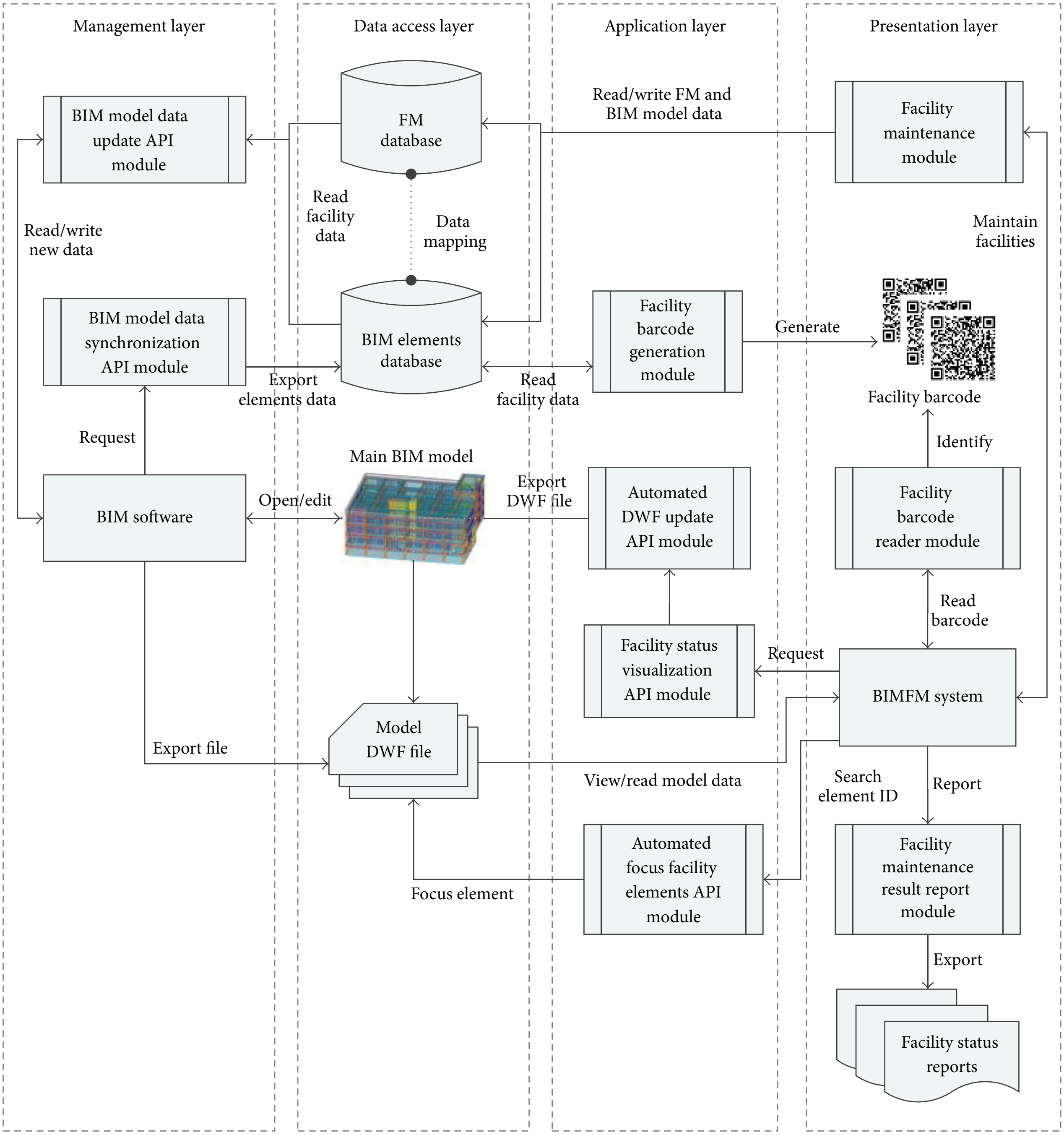


Figure 2: System and module framework of the BIMFM system.

the facility is lost or scrapped), the most recent maintenance date and the facility replacement date can be automatically updated for the corresponding BIM model. Therefore, BIM engineers and FM managers can directly access the updated facility maintenance information in BIM software.

5.2.5. Automated Updated DWF File API Module. This module is mainly to allow users to quickly access the latest BIM models in the BIMFM system through the updated whole or separated DWF file. When the size of BIM models increases, system performance slows down. A solution is to decompose whole BIM models into smaller BIM models (exported as separate DWF files) for improved system performance. Models may be decomposed according to a floor or a specific area. Furthermore, the module will update the separated DWF file automatically when any information changes in the BIM model.

5.2.6. Facility Status Visualization API Module. The module provides the visualization functionality for FM status through

Table 1: Description of color usage in BIM model.

Color usage	Description
Green	The facility's maintenance work has been completed and the result is satisfactory.
Red	The facility's maintenance problem has been identified, but the result is not satisfactory.
Yellow	The facility's maintenance work has been out of schedule and the facility's maintenance work has not yet started.
Blue	The facility's maintenance work has been out of schedule and the facility's maintenance work has not been completed.

a visualized BIM model. Through a systematic FM analysis of test results, the module displays different colors to illustrate various conditions and FM status (such as qualified inspection, required repair status, and obsolete facility). Users can access the overall different maintenance conditions and FM status quickly through the visualized BIM model. Table 1 displays the colors associated with each status.

There are two subsystems in the BIMFM system. The first subsystem is the API monitoring subsystem for BIM engineers located on the server side. This subsystem deals with integration services of BIM models in the BIMFM system. These services include BIM elements database initialization, updating facility maintenance information, and visualizing the maintenance status of facilities. Another subsystem is the maintenance subsystem located on the client side. This maintenance subsystem is developed for FM staff and FM managers to deal with FM operations in the facility's location, such as reading the barcode attached to the facility, recording FM, and reporting FM results.

5.3. System Process Description. There are four processes used in the BIMFM System including the system initialization process, FM information monitoring process, maintenance implementation process, and API information processing process (see Figure 3).

5.3.1. System Initialization Process. The purpose of the system initialization process is to provide adequate information on a facility for maintenance operations. The BIM model must provide all information and related models (DWF files) on a facility as an information requirement for facility maintenance operations. When the BIM model is input with complete facility information, the BIM engineer needs only to use BIM software (such as Revit) to open the BIM model and run the BIMFM API monitoring system to complete the setup work. When the BIM engineer opens the API monitoring system, the system will automatically determine whether the BIM model is run in the program for the first time. If so, the system will automatically insert all the facility elements information into the BIM elements database and the BIM 3D model (such as the model of each floor and a special area model) for exporting to the DWF file in the BIMFM system. If not, the system will only automatically update any new facility elements information to the BIM elements database and update the changed DWF file.

5.3.2. FM Information Monitoring Process. When the system initialization process is completed, the system will automatically enter the FM information monitoring process. The major purpose of the FM information monitoring process is to check and track whether the user requests the server to update API information. When the demand signal is transmitted to the system by a user, the system will begin to update API information again in the server. Furthermore, the BIM engineer can stop the FM information monitoring process at any time. All API services in the application layer of the BIMFM system will stop operation when the FM information monitoring process is stopped.

5.3.3. Maintenance Implementation Process. During the maintenance implementation process, the maintenance list varies according to the maintenance task categories. The design lets FM staff work on maintenance operations effectively according to the task categories and maintenance list. FM staff can utilize the webcam-enabled Tablet PC to access the BIMFM system and show all the task categories and maintenance lists based on different levels of access. After FM staff selects a particular task category, the system shows the history task form for that category. FM staff can view the other task forms, edit the unfinished task form, or add a new task form. When FM staff selects or adds a task form, the system retrieves facility information from the BIM elements database based on the task types. Furthermore, a list of all related maintenance and results will be illustrated with the BIM model for FM work preparation. FM staff can access inspection information and the maintenance status effectively. During the maintenance implementation process, FM staff can use the system directly and read the QR code attached to the surface of the facility. When the system receives the facility ID, the system automatically displays the facility's basic information and historical maintenance data in the BIM model. Furthermore, the facility's BIM model will be selected, focused, and highlighted using different color. User can obtain basic information on the facility by scanning the QR code attached to the facility, clicking the BIM model, or selecting from a maintenance list. After selecting the facility through one of the three methods, the FM staff can handle maintenance work and record the status and result of maintenance. Finally, all maintenance records and information are stored in the FM database.

5.3.4. API Information Processing Process. During the process of maintenance operations, the maintenance status can be enhanced by color visualization in the BIM model through the API information process. Through the functionality that visually depicts the status of maintenance list items, the system will send the updated signal automatically to the server side of the BIMFM system. The system will start API information processing if the BIMFM system is running during the FM information monitoring process. First, the system will get related maintenance information from the maintenance list in the FM database and update the main

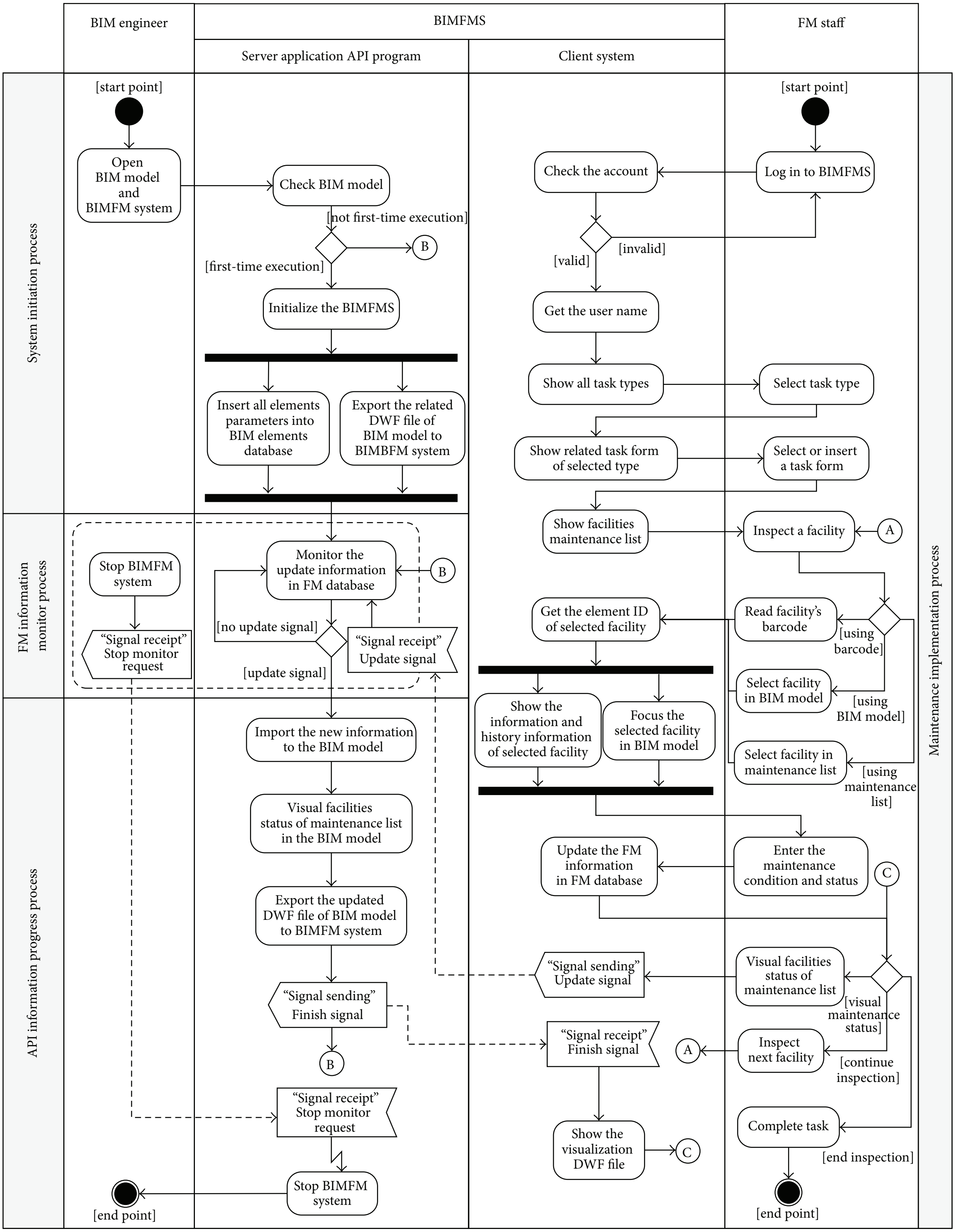


Figure 3: The system process flowchart used in the BIMFM system.

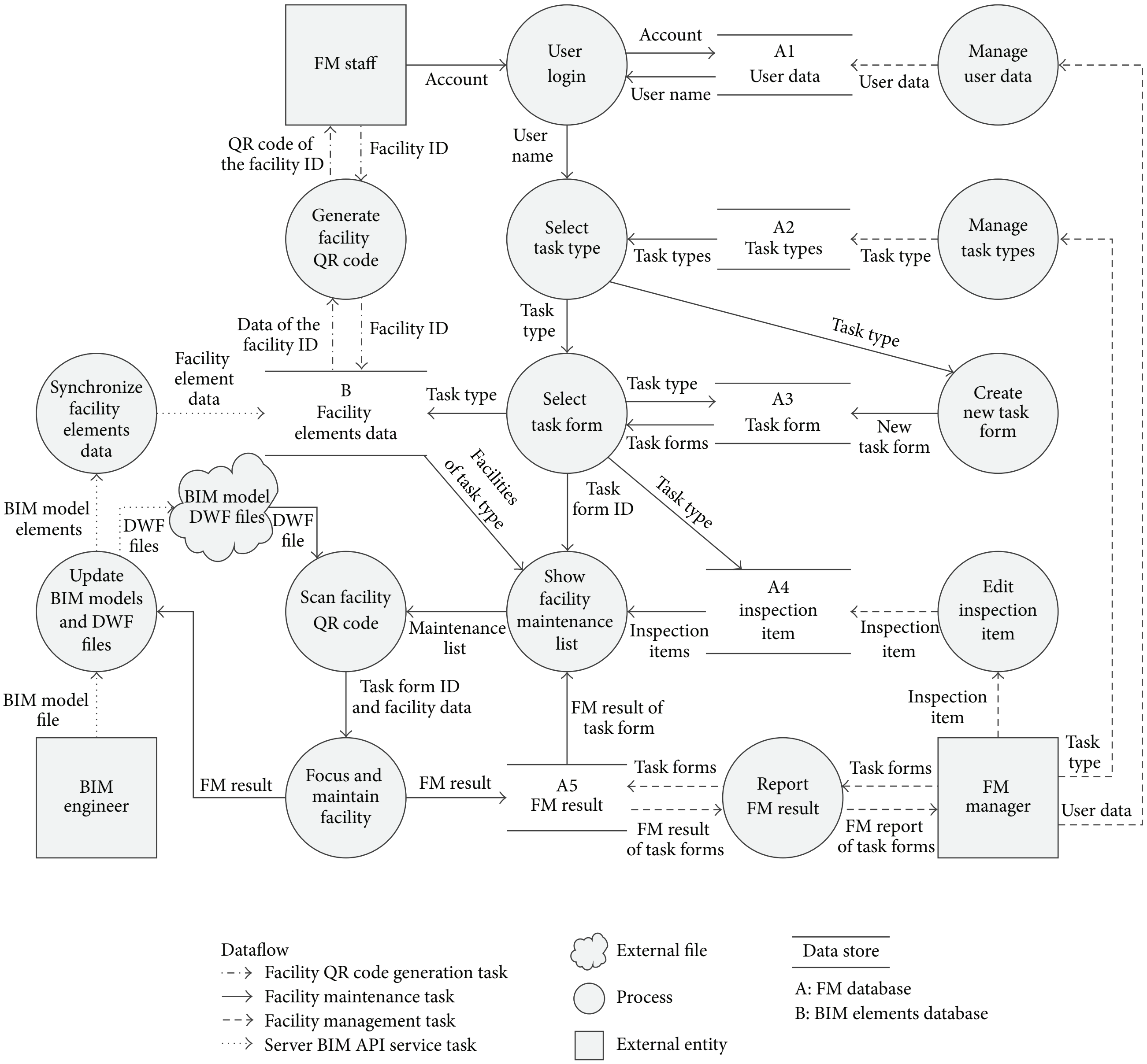


Figure 4: The information flow used in the BIMFM system.

BIM Model through API information processing. After the maintenance list is updated in the database, API creates a new 3D view automatically; the 3D view assists with color visualization of the facility based on the maintenance status. The 3D BIM model of facilities in the selected task form will be displayed in a color based on maintenance status, while the rest of the BIM model elements will be displayed in translucent white to enhance the visualization effect. All color visualization is described in Table 1. Finally, the system will export the completed 3D view BIM model to the DWF format automatically, store DWF files in the server side, and return the completed signal to the client side. The system will automatically connect to the server and open the visual DWF files to assist in the visual effect of the maintenance status when the client receives the completion signal.

5.4. System Information Flow Description. There are three external entities in the BIMFM system. They are entity *BIM engineer*, entity *FM staff*, and entity *FM manager* (see Figure 4). This section describes each external entity in the BIMFM system.

The entity *BIM engineer* is primarily responsible for starting the BIMFM system in the BIM API service on the server side and opening the applied BIM model in the system. This is called the BIM API service task in the study. In the beginning, entity *BIM engineer* must use the BIM software to open the BIM model and also start the BIM API service. When the BIM model is imported to the BIMFM system, the process *update BIM models and DWF files* will automatically update the BIM model information (including BIM model elements and the DWF files). The process *synchronize facility* *elements data* will check the updated facility element data first. The needed updated information will be imported into the *store facility elements data* in the BIM elements database. All updated DWF files will be saved directly in an external file.

The entity *FM manager* is primarily responsible for handling the BIMFM planning and management work. The operation is called the FM task in the study. The FM tasks include various operations and procedures of management (including processes such as *manage user data*, *manage task types*, and *edit inspection item*). The entity *FM manager* can handle all system data management during the processes. All changed and updated information will be imported into the corresponding data store of the FM database. Furthermore, the entity *FM manager* can select multitask forms to export as a report. The process *report FM result* will acquire the related information based on selected task forms from table *FM result data* of the FM database. Furthermore, the process *report FM result* analyzes the information, compiles it into report format, and sends back a final report to the entity *FM manager*.

The entity *FM staff* is primarily responsible for handling the facility QR code generation task and facility maintenance task. The facility QR code generation task is developed to handle the preparation of QR code work. Entity *FM staff* may create one QR code label or a set of QR code labels for FM use. The process *generate facility QR code* will obtain related information on the facility from the *BIM elements data* table based on the facility ID, send the information for QR code coding, create the QR code image file for the facility, and send it back to entity *FM staff*. The facility maintenance task handles various operations and procedures of FM. In the beginning, the process *user login* will check the user's authority based on the user name and password in the store *user data*. The process *select task type* will show task types in the store *task types* for the selection if certification is passed. The process *select task form* will show the related FM task form based on task type for FM staff selected. If the maintenance work is a new activity, the process *create new task form* will create a new task form based on the selected task type and save it in thetable *task form data*. After entity *FM staff* selects a task form, the process *select task form* will acquire the necessary facilities list from the table *facility elements data* in the BIM element database and acquire necessary inspection items from table *inspection item data* in the FM database. The facilities list and inspection items integrated with the selected task form ID will be imported into the show process *facility maintenance list*. Furthermore, the show process *facility maintenance list* acquires maintenance results from table *FM result data* in the FM database. The process *show facility maintenance list* will arrange information as maintenance list and export information to the process *scan facility QR code* after acquiring complete information. When entity *FM staff* scans the QR code of the facility, the facility QR code process will decode the QR code automatically to send task form ID and facility data into the process *focus and maintain facility*.

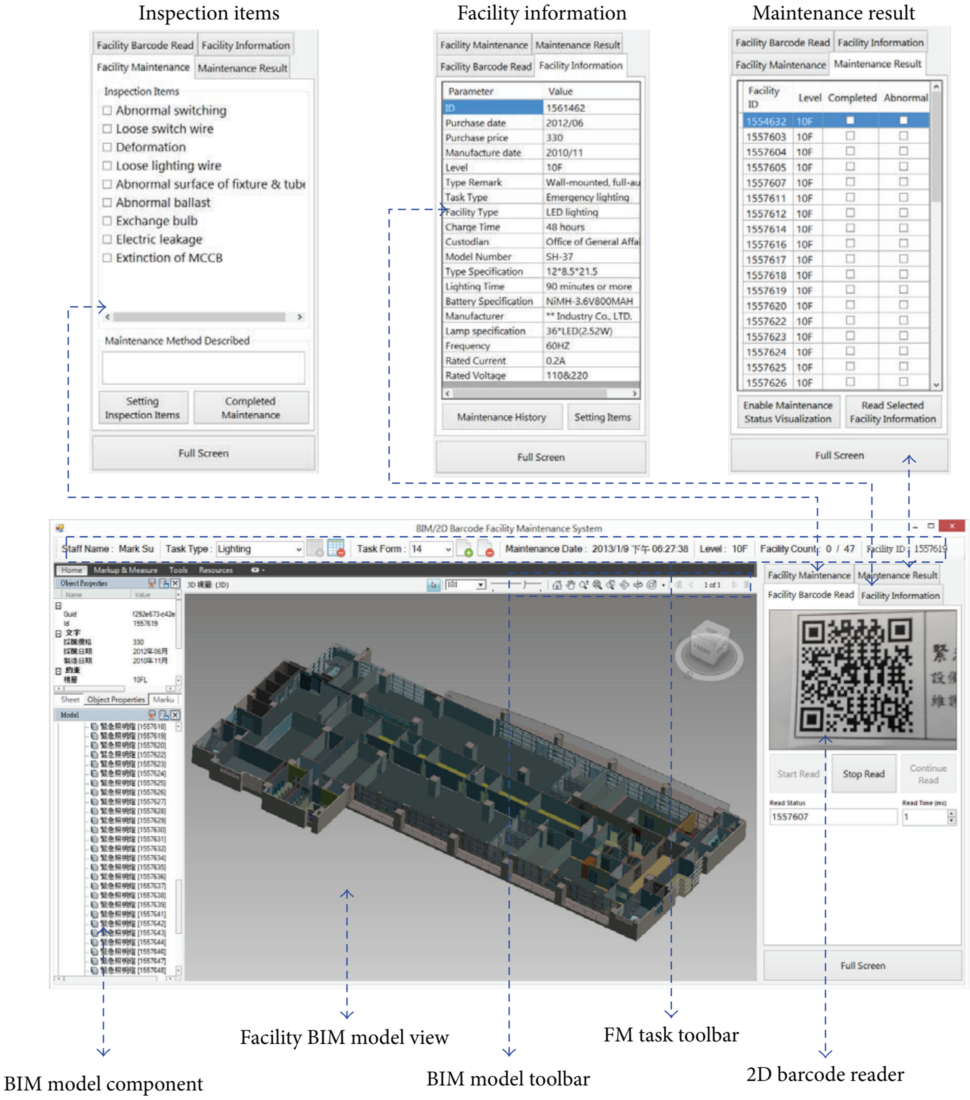
The process *focus and maintain facility* will zoom in and highlight the BIM model of the facility automatically when it receives the facility data. Final maintenance results will be updated in the table *FM result data* in the FM database when entity *FM staff* finishes the maintenance work and sends back the process *update BIM models* to update facility status in main BIM model. The process *update DWF files* in the BIM API service will update all changed DWF files automatically, save them in the external file, and send DWF files back to the process *scan facility QR code* to let FM staff review the visualized DWF file if FM staff requests facility status visualization.

Integrated with the above design concept, more complex operating procedures of FM are simplified and developed in the BIMFM system. One of the major characteristics of the BIMFM system is to provide users with easy-to-use visualization for handling FM work. By clicking the list, each task form will show the list of facilities requiring maintenance, historical maintenance information, and the status and condition of facilities maintenance. By scanning the QR code attached to the facility, the corresponding BIM models are linked and illustrated quickly and effectively in facility location. Finally, all maintenance results are sent back and saved in the main BIM model. The proposed approach provides a means to update the facility information of the BIM model and FM information synchronization. Finally, in order to let FM staff applies the system easily and effectively, the layout of the system is designed based on FM staff's suggestions. Figure 5 shows the graphical user interface (GUI) of the BIMFM system.

6. System Validation

6.1. Case Study. For the case study, the proposed BIMFM system of this study was applied to a building in Taiwan; that is, a BIMFM system was utilized for the FM of the case study building, which contained approximately 20 facilities that had to be managed and inspected. Usually, the FM work was executed every month. Existing approaches for tracking and managing the FM work relied on paper-based records. The bulk of the FM work was paper-based and documented by repeated manual entry, although an FM system was developed for a standalone software application. Therefore, the FM staff in the FM division utilized the BIMFM system to enhance the FM work in the case study.

After the critical facilities were selected for FM work, each QR code label was made, and the unique ID for each facility was entered into the BIMFM system database for quick search. During the FM process, the QR code label was scanned for basic information about the facility before the FM work started. Before the FM work began, the FM staff could check the facility list from webcam-enabled tablets, refer to the relevant information, and begin preparation work without printing any paper documents. During the FM process, the FM staff scanned the QR code label first (see Figure 6(a)). The BIMFM system showed the basic information and the BIM model of the facility after scanning the QR code label. The FM staff could then check further detailed information like maintenance instructions, notifications, and accessories list, all of which were supported by BIMFM



Inspection Items
- ☐ Abnormal switching
- ☐ Loose switch wire
- ☐ Deformation
- ☐ Loose lighting wire
- ☐ Abnormal surface of fixture & tube
- ☐ Abnormal ballast
- ☐ Exchange bulb
- ☐ Electric leakage
- ☐ Extinction of MCCB

Maintenance Method Described

Parameter	Value
ID	1561462
Purchase date	2012/06
Purchase price	330
Manufacture date	2010/11
Level	10F
Type Remark	Wall-mounted, full-au
Task Type	Emergency lighting
Facility Type	LED lighting
Charge Time	48 hours
Custodian	Office of General Affa
Model Number	SH-37
Type Specification	12*8.5*21.5
Lighting Time	90 minutes or more
Battery Specification	NiMH-3.6V800MAH
Manufacturer	** Industry Co., LTD.
Lamp specification	36*LED(2.52W)
Frequency	60HZ
Rated Current	0.2A
Rated Voltage	110&220

Facility ID	Level	Completed	Abnormal
1554632	10F	☐	☐
1557603	10F	☐	☐
1557604	10F	☐	☐
1557605	10F	☐	☐
1557607	10F	☐	☐
1557611	10F	☐	☐
1557612	10F	☐	☐
1557614	10F	☐	☐
1557616	10F	☐	☐
1557617	10F	☐	☐
1557618	10F	☐	☐
1557619	10F	☐	☐
1557620	10F	☐	☐
1557622	10F	☐	☐
1557623	10F	☐	☐
1557624	10F	☐	☐
1557625	10F	☐	☐
1557626	10F	☐	☐

BIM/2D Barcode Facility Maintenance System

Staff Name : Mark Su
Task Type : Lighting
Task Form : 14
Maintenance Date : 2013/1/9 下午 06:27:38
Level : 10F
Facility Count : 0 / 47
Facility ID : 1557619

Read Status: 1557607
Read Time (ms): 1

Figure 5: GUI of the BIMFM system.

(see Figure 6(b)). After the FM work, the FM staff entered the results of maintenance, edited the description in the tablet, and provided the updated information to the system (see Figure 6(c)). When a facility required repairs, the system also provided the manufacturer's problem information for immediate reference. Finally, the facilities manager and the authorized FM staff accessed the updated information simultaneously from their offices (see Figure 6(d)).

6.2. Evaluation and Results. Overall, the field test results indicate that the integration of BIM and 2D barcode labels is an effective tool for the FM of a building. All 2D barcode labels survived use in the pilot test over the two-month testing period. Approximately 25 users participated in field trials of the FM process. The BIMFM system was installed on the main server in the FM division of the building.

During the field trials, verification and validation tests were performed to evaluate the system. The verification test aims to evaluate whether the system operates correctly according to the design and specification, while the validation test assesses the usefulness of the system. The verification test was carried out by checking whether the BIMFM system could perform the tasks specified in the system analysis and design. The validation test was undertaken by asking selected case participants to use the system and provide feedback by answering a questionnaire. Twenty-five participants were involved in the evaluation test. To evaluate the system function and the level of satisfaction with the system's capabilities, the users of the system were asked to grade the conditions of system testing, system function, and system capability, separately, in comparison with the typical paper-based FM approach. Some comments for future improvements to the BIMFM system were also obtained from the case participants through the user satisfaction survey. Finally, Table 2 shows a comparison of the current approach and the proposed system.

Table 2: Comparison of current approach and proposed system.

Item	Current approach		Proposed approach	
	Method	Average time	Method	Average time
Edit the defect problems of the facility	Edit the defect problems by paper-based sheet	12–20 sec	Edit the defect problems through the BIMFM system	6–12 sec
Find basic information on facility for reference	Review maintenance data on paper-based sheet	12–23 sec	Access basic information on a facility directly by accessing and clicking BIM model	7–13 sec
Refer to relevant historical maintenance information	Refer to paper-based maintenance lists and reports	12–18 sec	Click BIM model and refer to historical maintenance information directly	6–12 sec
Maintenance information updating	Identify and record results on a checklist, then re-enter at the office	42–52 sec	Real-time data entry in the system during maintenance process	22–42 sec
Mark the inspection problems at the facility location	Refer the paper-based maintenance condition and status sheet	1–1.5 min	Illustrate overall maintenance conditions and status of FM quickly through visualized BIM model	40–50 sec

(a) FM staff scanned the QR code and accessed BIM model of facility

(b) FM staff referred to the maintenance list and reviewed the BIM model in the tablet

(c) FM staff inputted and updated the maintenance records in the tablet

(d) FM manager accessed maintenance records directly using BIMFM system

Figure 6: FM staff using webcam-enabled tablet to scan QR code label for FM work in the case study.

The percentage of satisfied users (96%) obtained from the user satisfaction survey indicates that the BIMFM system is quite adaptable to current FM practices in a building and is attractive to users. The overall result implies that the BIMFM system is considered well designed and is able to enhance current time-consuming FM processes. The satisfaction rate exceeding 88% also indicates that the visual BIM model that provides FM support is very helpful. The 92% rate of satisfaction with the integration of the QR code in the BIMFM system for the direct access of the BIM model also indicates that this integration of the QR code is considered effective and necessary. Moreover, no additional work is required to complete the documentation beyond the data collection process. The advantages and disadvantages of the BIMFM system identified from the pilot study are identified.

In the cost analysis, the total cost of the equipment applied in this study was $3,500 US dollars (including an 11-inch webcam-enabled tablet and one PC server). Most personal computers can generate and print QR code labels using free software. Furthermore, there is no additional cost for the QR code reader hardware because most tablets are equipped with cameras that enable 2D barcode scanning. The experimental results demonstrate that the BIMFM system can enhance the visual FM process significantly and effectively when using a BIM approach that is integrated with 2D barcode technology. The use of these technologies significantly improves the overall performance of maintenance operations.

6.3. Limitations and Barriers. The findings of this case study revealed several limitations of the BIMFM system. The following are inherent problems recognized during the case study.

(i) It is difficult for new users to operate the BIM model in the BIMFM system. Some FM staff are initially unfamiliar with BIM models. As it usually takes time to learn how to use BIM models, the use of the BIM system in the case study initially lengthened the FM operation over the traditional approach, since users required time to find the corresponding BIM model and fill out the FM information in the BIMFM system. After the user becomes skilled and familiar with the BIM model, the time required by the current approach and the proposed system becomes almost exactly the same as in the previous FM operations.

(ii) If BIM models do not exist for the purpose of construction management during the construction phase, the BIM approach integrated with FM will not likely be implemented within the BIM environment. Most FM companies do not want to spend the required time and cost to use BIM for only FM work on building projects.

(iii) As QR code labels attached to outdoor facilities are easily damaged because of external environmental pollution (such as dust and rain), it is necessary to consider and enhance the protection and the waterproofing of the QR code labels.

(iv) The QR code technology's short-read distance range was the primary limitation in the case study. In some facilities, the QR code labels were installed up high where FM staff could not easily reach them. Therefore, it is recommended that the QR code label be attached at a lower space on the facility for easier scanning or, alternatively, that the QR code label be associated with the BIM models for all of the facilities in the room and placed at the entrance of the room. A user can then scan the QR code label at the entrance of the room to find and select directly the BIM model of a facility.

(v) The best read distance of QR code labels is about 3 meters (in a straight line). Based on the case study, the scanning distance varies depending on the tablet camera's resolution. Furthermore, the webcam-enabled tablet cannot identify a QR code label and read the information if the lighting is too low. The QR code labels cannot be recognized if the corner side of the position-detection pattern block position is damaged or polluted.

(vi) In consideration of the limited storage capacity of the tablet and the notebook, it is suggested that the BIM engineer create the DWF files in the database in advance. However, the file size of the DWF will affect the performance of the BIMFM system directly and evidently. The impact includes the time of reading of the DWF files, the time to search for the facilities, and the smoothness of the system operation. When the DWF file is too large (more than 100 MB), it cannot be opened. Therefore, the main BIM model of the whole building should be exported and separated into many DWF files for each floor. When the FM staff execute the FM work, the system opens the DWF file for the floor only after the FM staff scan the QR code for the facility. Furthermore, the FM staff can quickly refer to the separated DWF files of the floor for FM work.

(vii) Based on the case study, BIM engineers are required to update the BIM models continuously during the maintenance and operation phase. When new equipment or facilities are purchased, the BIM engineers must create an FM element for the new equipment in the BIM model for future maintenance use. Furthermore, communications between the FM maintenance staff and the BIM engineers are necessary and important during the process. The FM staff should inform the BIM engineers about any problems regarding the BIM models. After the BIM engineers correct the BIM models, they must also notify and discuss it with the FM staff. The BIM models require constant maintenance and updates. Another important issue is the quality management of the BIM models. Although the study proposes using the BIMFM system as a means of helping FM staff handle visual facilities maintenance and management work, the advanced management procedures and mechanisms for the quality management of the BIM models for FM must be identified and developed in the future. Particularly, the management mechanisms for updating the BIM models should be developed as the next step of BIMFM system development.

7. Conclusions

The BIM approach, which is applied to retain facility information in a digital format, facilitates easy updating of FM information in a BIM environment. Although many practical cases of using BIM during the maintenance management stage exist, one problem is that it is not easy for FM staff to find the corresponding FM element in the BIM model for maintenance management during the phase. In order to assist FM staff with obtaining the corresponding FM element in the BIM model for FM in an automatic and effective manner, this study develops a BIMFM system that integrates 2D barcode technology to connect automatically to the BIM models. The mobile automated BIMFM system not only improves FM efficiency but also provides a real-time service platform during the FM process. In the case study, 2D barcode readings increased the accuracy and the speed of the BIM model searches, indirectly enhancing performance and productivity. The FM staff used webcam-enabled tablets to enhance the FM work seamlessly at facility locations, owing to the system's searching speed and ability to support related information collection and access during the FM process. Meanwhile, on the server side, the mobile automated BIMFM system offers a hub center to provide the FM division with real-time monitoring capacity during the FM process. Integrated with the characteristics of 3D BIM model illustration and BIM parametric design, the mobile automated BIMFM system quickly shows the necessary maintenance information by using a facility's BIM model based on the selected task type and clearly presents the position and the height of the selected facility. The main contribution of this study is to help FM staff obtain the corresponding FM element in the BIM model in an automatic and effective manner by integrating BIM with 2D barcode technology. Furthermore, the proposed solution aims to enhance the tracing and recording of FM status through the visualized and colorized BIM model.

In the case study, the application of the mobile automated BIMFM system helped to improve the FM work of a commercial building in Taiwan. Based on the experimental results, this study demonstrated that BIM technology has the significant potential to enhance FM work. The integration of BIM technology with 2D barcode technology helps FM managers and FM staff to effectively track and control the whole FM process. Compared with current approaches, the combined results demonstrate that a BIMFM system can be a useful mobile BIM/2D barcode-based FM platform. Based on the case study findings, the BIM models must be constantly updated and corrected. Another important issue is the quality management of the BIM models. The advanced management procedures and mechanisms for the quality management of the BIM models for FM need to be identified and developed in the future. Such an endeavor will be the next step in BIMFM system development. Finally, the limitations, encountered problems, and suggestions are discussed based on the implementation of the case studies in this study. Despite the challenges indicated above, the promising results shown in this study demonstrate the great potential of the proposed system as a means of aiding the FM of buildings.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

BIM Based Virtual Environment for Fire Emergency Evacuation

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Recent building emergency management research has highlighted the need for the effective utilization of dynamically changing building information. BIM (building information modelling) can play a significant role in this process due to its comprehensive and standardized data format and integrated process. This paper introduces a BIM based virtual environment supported by virtual reality (VR) and a serious game engine to address several key issues for building emergency management, for example, timely two-way information updating and better emergency awareness training. The focus of this paper lies on how to utilize BIM as a comprehensive building information provider to work with virtual reality technologies to build an adaptable immersive serious game environment to provide real-time fire evacuation guidance. The innovation lies on the seamless integration between BIM and a serious game based virtual reality (VR) environment aiming at practical problem solving by leveraging state-of-the-art computing technologies. The system has been tested for its robustness and functionality against the development requirements, and the results showed promising potential to support more effective emergency management.

1. Introduction

Building emergency management can be generally illustrated as an integrated scientific methodology to provide reasonable solutions for human safety in extreme environments [1] and this is particularly significant in addressing the regrettably common occurrence of fire disaster, which directly relates to the lives and property safety of all occupants in the building [1, 2]. Recent relevant research has identified that the cause of a high proportion of emergency casualties has a direct link with the delayed evacuation service of the facility [3, 4], which can be caused by the lack of real-time two-way information updates; building users (and visitors) in an emergency situation cannot get the real-time evacuation route, while the external control centres lack real-time situation updates, for example, the real-time location of building users.

Traditionally, fire emergency management utilizes fire drills or experiments to enhance fire emergency planning. However, there has been little discussion about awareness of the safety situation in a fire drill and the resource costs for emergency experiments, which influence the validity and generalizability of their results [5]. Moreover, the above-mentioned traditional measures can only provide solutions after the completion of building design; hence, it is difficult to detect the conflicts (to fire emergency evacuation plan in practice) early during the design stage, and the follow-on modification process (to address fire emergency issues) would be very time consuming and costing.

BIM promotes integration and collaboration which allows applications at different stages of the building life cycle to be effectively “linked” through the shared information, but a significant number of current BIM developments have been directed to design collaboration and the subsequent economic benefits for design professionals; dedicated BIM based solutions for building emergency management are relatively less focused [6]. BIM can play a significant role in providing real-time and accurate building information under an emergent situation due to its comprehensive and standardized data format and integrated process.

Although several recent research studies on fire emergency management have been trying to embed human behaviour modelling into building emergency management, there is still a lack of studies that can adequately and precisely represent human behaviour in emergent situation [7] and conduct effective information interaction between the building and the building user [8]. Kobes et al. proposed to use virtual games to get a real-time observation of human behaviour in a fire as video recording of real fire evacuations are rare [9].

This paper introduces a framework that utilizes BIM as a building information provider to work with serious game technologies to build an adaptable virtual reality environment with the purpose of enhancing fire evacuation plans throughout the building life cycle. The focus lies on how to utilize updated building information with virtual reality technology to provide real-time fire evacuation guidance. The developed virtual reality environment can also be utilized during the design stage by leveraging the engagement of a wider audience, such as general end-users, who are the genuine users of a building and play a vital role in assisting professionals to achieve satisfactory building emergency designs and follow-on services.

The following contents are organized as follows. Section 2 explains the related work; Section 3 shows the design and implementation for a BIM-VE (virtual environment), including a two-way information channel between the building information model and the serious game environments, supporting computing hardware, and the overall server/client based infrastructure and information flow. Section 4 explains the case application for fire evacuation, including algorithm development and implementation for BIM based dynamic emergency route planning on multiple platforms during different stages of building life cycle, and dynamic scenarios generation with building semantic information for fire emergency training. System testing and evaluation are detailed in Section 5. The discussion follows and the conclusion and future work are given at the end.

2. Related Work

Building emergency management concerns several main aspects, such as emergency preplanning, emergency psychological human behaviour, and timely information communication [1, 10]. Emergency preplanning is an action plan devised as a precautionary measure before any disaster and is activated in response to major incidents only. The normal approach to address emergency preplanning includes preplanning drills and digital preplanning [1, 5]. The preplanning drills are to record the behaviour of participants (as evacuees), which usually includes the completion of a postevacuation questionnaire to supplement and supply the results that are hard to be observed, such as perception of emergency cues during the drills. Several research projects utilized this approach to study the behaviour of store shoppers [11, 12], with some interesting findings, such as the observation that some exits were not used since there was no staff to direct there and some evacuees showed a reluctance to pass disabled evacuees, which was one of the reasons for an increase in evacuation time. Although taking recordings of drill participants, followed by a questionnaire analysis, is the most common method to support the emergency preplanning, it often covers only singular aspects of human behaviour. Also, the contents of a questionnaire are sometimes not necessarily useful because participants know they are not in a dangerous situation and therefore suffer no cognitive emergency stress. In addition, real world emergency drills cannot be conducted regularly and the participants are also limited to the people who are in the building during the emergency drill [5].

In terms of digital preplanning, an emergency preplanning semantic retrieval system for facility managers was implemented to retrieve related knowledge from relevant management documents [13]. Yan built a core library which can be used to modify, query and match, judge and evaluate, and classify and analyse the preplans. Through this digitalized emergency preplanning, the end-users can create an evacuation scheme and monitor the evacuation process in real time [10]. Nonetheless, the abovementioned digitalized preplans heavily rely on the complicated database which sometimes can be difficult to be maintained and updated to a satisfactory level to retrieve meaningful results for the end-users. Rüppel and Stuebbe combined building information and indoor navigation systems on mobile devices to improve fire emergency plans and route finding for complex buildings [14]. However, the building information for such a system is static and limited, which means it cannot dynamically change the shortest path displayed according to the constantly changing situation during a fire emergency. Lastly, this system was limited to specific mobile devices used by fire fighters rather than common mobile devices such as smart mobile phones utilized by general end-users of the building.

Incident analysis has revealed that there is a link between a delayed evacuation and a high number of fire deaths and injuries, especially in residential and high-rising buildings [15]. One of the most widely known examples illustrating this link is the 2001 terrorist attack on the World Trade Centre (WTC). Several methods were employed for information gathering such as first-person accounts taken from newspapers, radio and television programmes, e-mail exchanges, and a variety of websites, questionnaires, telephone interviews, and face-to-face interviews [16]. The comprehensive process of data collection mentioned above consumed a huge amount of time and money and is restricted to this specific scenario. According to Kobes et al., employing a serious game to collect information on human behaviour in a simulated fire disaster could be an efficient method to save time and money [9].

Recent computing developments have enabled computer gaming systems to be utilized for building emergency management [6]. A BIM based serious game system was designed to explore human behaviour during a fire emergency [8], but the file system they used to transfer building information to the game environment is semiautomatic. If the participants in the virtual experiment adapt and get familiar with the scenarios, they have to manually stop the serious game and change the scenario, which makes the participants lose focus. Other researchers are working on the combination of human emergency behaviour with simulation technology [7, 17]. Li et al. proposed a prototype of a behaviour based human motion simulation for fire evacuation procedures [17]. Ren et al. developed a virtual system with spreading fire and smoke to simulate a fire evacuation based on the interaction between AI and the virtual fire environment [7]. However, questions have been raised about how to precisely represent emergency behaviour to simulate a fire evacuation [5]. According to

Sime [18], some human behaviours during an evacuation have not been sufficiently understood and require further study to build a connection between the fire evacuation and fire safety engineering. Lin et al. enhanced emergency path planning by utilising the semantic information from IFC and the Fast Marching Method [19]. But the geometric and semantic information defined in the IFC have to be imported into the specific virtual environment manually, which is time consuming and ineffective.

3. BIM Based Virtual Environment (BIM-VE)

3.1. Virtual Reality Equipment in Cardiff University. Virtual environments (VEs) are three-dimensional, computer generated environments that occur in the real world but can be manipulated by the end-users [20]. The virtual reality technology that can generate high quality VEs has been introduced to many fields to assist military training, industry product design, and serious academic investigation. Its ability to allow end-users to experience a range of threatening or dangerous situations without physical harm provides many potential benefits. Guo et al. used game and virtual reality technologies to develop a safety training platform to improve the safety of construction plant operations. They utilised Wii controllers to provide trainees with the hands-on practical tools that allowed them to conduct some construction plant tasks without physical danger in a virtual environment. Through this safety training, the trainees can understand operating processes, improve collaboration among operators, and identify safety problems on the construction site [21]. Similarly, Harris and Morgenthaler developed virtual prototyping simulation tools to demonstrate ground processing, depict real-time visualization of design, and plan aerospace missions in a 3D immersive visualization environment (IVE) [22]. Rüppel and Schatz have begun to design a BIM based serious game for fire safety evacuation simulations in the Darmstadt CES-lab [8]. Darmstadt CES-lab is a virtual reality lab that provides hardware support to generate virtual environments in the sense of an immersive system. As for the software component, a BIM-game engine is being built that utilizes a file based information interchange mechanism to transfer building information and simplify physical interactions between objects. However, the building information transferred via the BIM-game engine is semi-automatic and cannot be updated in real-time. With augmented reality, Koch et al. presented a conceptual framework that uses the camera of a mobile device to recognize natural markers (e.g., exit signs), which can mix the virtual and real environment to provide facility maintenance support [23].

The quality of a VE's representation varies greatly, but it is agreed that the more accurate details a VE can map with the real, the more immersive effects the end-users can feel. Suitable hardware for the expression of a VE has been implemented in Cardiff Virtual Reality Lab, which has been established at the Engineering School of Cardiff University. Cardiff VR Lab comes with an efficient VE in the case of an immersive system. It provides a natural interface between humans and computers by artificially imitating the way humans interact with their physical environment. The virtual reality equipment in the lab intends to enhance the main senses of the end-user which include sight, hearing, feeling, touching, and smell, utilising both the output of sensory information and input commands from the user. The output equipment (Figure 1) includes an immersive stereoscopic display, head mounted display (HMD), and a surround sound system. Input facilities include motion tracking sensors such as head tracking sensors and body tracking sensors, hand-held 3D navigation devices such as a Wii remote control or Razer Hydra joystick, a 2D navigation device such as a mouse and keyboard or a touch pad/phone, and devices that mimic the physical environment such as smoke fragrance and heat radiator.

In order for the VE to mimic the real environment, it must be able to integrate the sensory output of the environment to the real actions (navigation) of the end-users. It should couple the visual output (for perception of fire, tracking of moving characters, distance judging, space searching, and building environment estimation) and auditory output (for emergency recognition and localization) with the end-users' navigation (first person view, third person view, fly-through view, and manipulation of building objects). Ideally, the end-users in the VE are fully immersed and feel they are actually "present" in fire, to prevent them from making unrealistic decisions due to a lack of physical feelings in the VE [20, 24]. To achieve the above, the following capabilities are needed to immerse the end-users into the VEs:

(i) high-resolution, 24-bit colour, flicker- and ghosting-free, 3D stereoscopic display to maximize the visual stimulus of fire conditions (i.e., the 3D projector for group views and the head mounted display (HMD) for better personal view),

(ii) sound effects which should surround end-users to allow them to recognize and locate the emergency by appreciable fire factors such as shouting or crying people, fire alarm, and noise of the roaring fire,

(iii) motion tracking to use multiple parts of his body (e.g., hands, head, and legs) to interact with the VE to enhance the end-user's physical feeling; it also allows the display of a realistic avatar based on the profile of each end-user, which can closely imitate their actual movements and physical dimensions,

(iv) navigation devices that allow accurate direction pointing, fly-through, or walk-through in the environment and manipulation with building object like extinguisher,

(v) light source based rendering and photorealistic textures,

(vi) visual consistency (the building elements' position and appearance are predictable like in a real environment),

(vii) decreased disturbance from virtual and real world.

3.2. Overall System Architecture. The approach of triadic game design (TGD) proposed by Harteveld [25] indicates

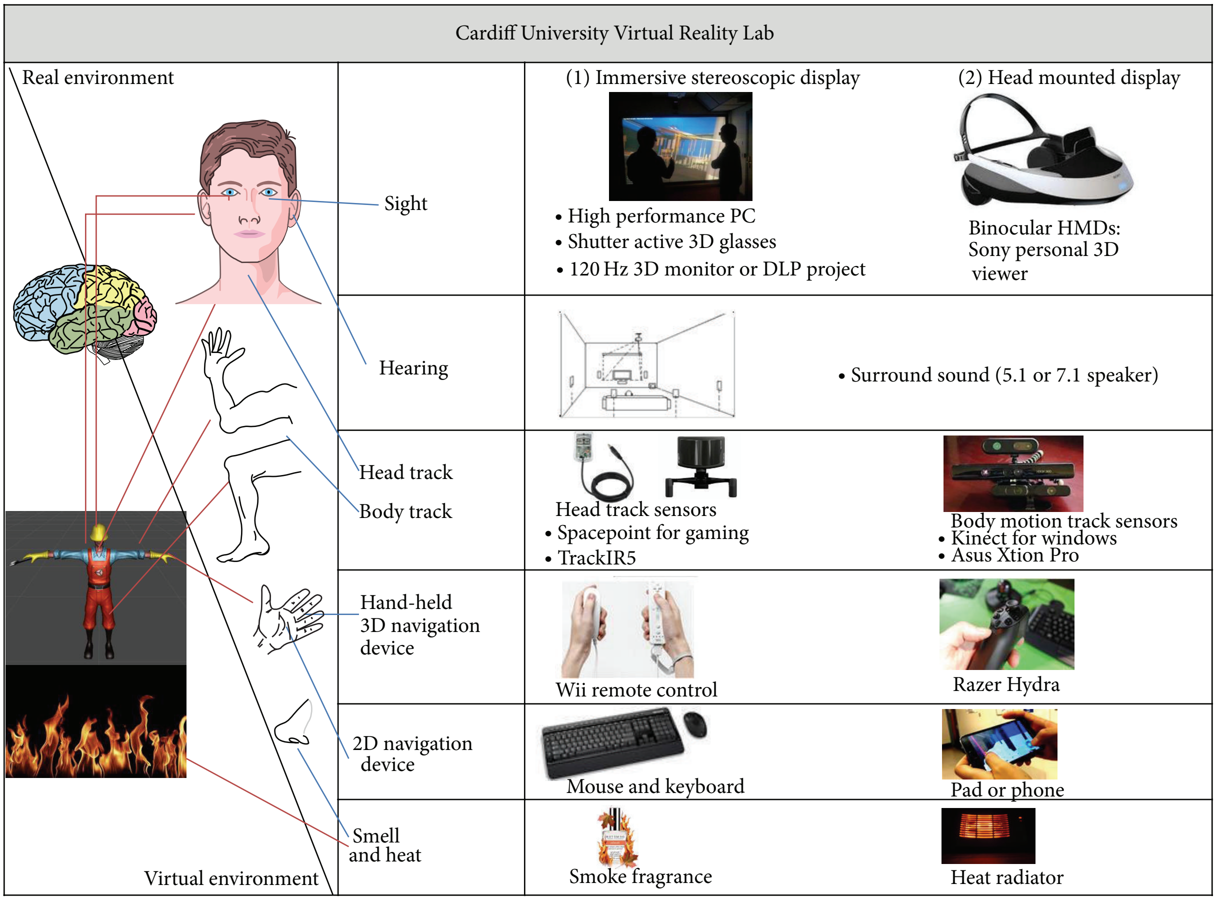


Figure 1: Existing and planned virtual reality equipment in Cardiff VR Lab.

that a virtual environment designer has to balance three independent worlds during the design process, that is, the world of reality, meaning, and play. The world of "reality" deals with how the virtual environment is connected to the physical world; the world of "meaning" focuses on the type of value that needs to be achieved; the world of "play" concerns the methods used to reach the objectives in the world of "meaning." The BIM based VE is shown in Figure 2, which illustrates what use-cases and which actors are involved and how they can be put together to achieve a balanced virtual environment.

Although video games have been available for almost thirty years, nonprofessional programmers have only recently been able to modify the virtual environments within games, because the editors used to modify them (game engine) have become very sophisticated but conversely easy to use [26]. As one of the most famous game engines, Unity3D is characterized by its multiple-platform system support and is available in free and commercial versions. With the Unity3D game engine, games can be exported as standalone applications for OSX and MS Windows, for consoles such as XBox and Wii, and for smartphones running iOS, Android, Blackberry, and Windows. More importantly, it supports web applets for online use, which can decrease the size of a game and promote its spread. Therefore, the Unity3D game engine can develop serious games for a wide range of end-users to gather measurable and quantifiable information for research (i.e., enhance quantitative research results). The Unity3D game engine provides very high quality shader, rendered textures, and interface to work with other platforms (including BIM modelling tools and virtual reality equipment) to make the virtual environment in the serious game comparable to the real and can be associated with an interpretative approach where the participants' point of view is utilised to understand opinions and associated results (i.e., improve qualitative research results).

Based on TGD framework, the proposed system utilizes a BIM authoring tool (Autodesk Revit) as a building information provider to work with Unity3D game engine and an AMP (Apache + MySQL + PHP) database to produce an adjustable virtual reality environment throughout the building life cycle. The system allows the involvement of the end-user in refining the building emergency plan and can provide them with effective evacuation training and guidance through various commonly available mobile devices.

The system architecture comprises three interconnected components (Figure 3).

(i) A data component contains the AMP database and Revit software. The component is controlled by an

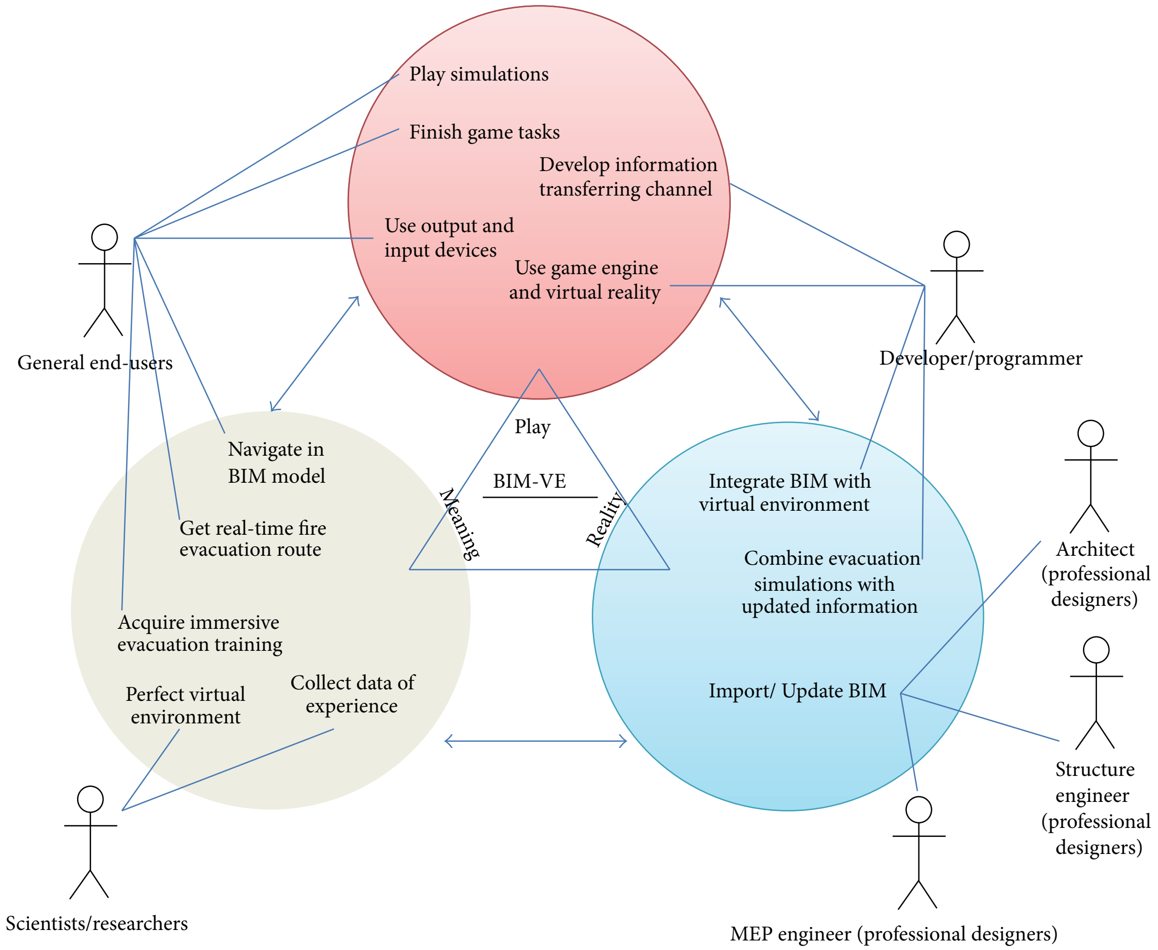


Figure 2: TGD based framework to develop BIM based VE.

administrator to generate semantic and geometric data and store it in the database to build a two-way and dynamic information flow for real-time fire evacuation routes and training.

(ii) A Unity server component connects Unity clients into an instance and feeds those clients the available data which is created in the data component.

(iii) Unity clients are the interfaces that immerse the end-users into the virtual environment (as an instance) which is generated by the Unity server. Clients work in different platforms with appropriate input and output devices, that is, Windows or Mac operating systems that use high-resolution monitors with keyboard and mouse, 3D stereoscopic projector with Razer Hydra joystick, Hand Mounted Display (HMD) with Microsoft Kinect Sensor, mobile platform using iOS or Android with touch screen and built-in camera, or web based environment that allows users to connect to the server through their web-browser.

Specifically, the data component is the main part in the automation of the data transmission between the building information model (in Revit) and the serious game (in Unity3D server and clients) by means of C# based APIs connected to an AMP database. The AMP database is the central hub to collect and transfer all of the required building information, which internally develops a two-way information channel between the building information model and the serious game. It initiates the data transmission process between the building information in Revit and the required information in the AMP database. The Revit model is separated into FBX geometric model and a semantic information file. The AMP database then feeds and maps all of the building information (i.e., geometric and semantic building information) in Unity3D server based on the object IDs of the FBX model and synchronizes Unity3D server with the available clients in line with remote procedure calls (RPC). For transferring information from Unity3D to the Revit model, AMP firstly receives the altered semantic information from the virtual game environment and feeds it back to Revit. Revit then reads the changes from AMP database and compares the two semantic information sets to update the appropriate BIM components.

In addition, the Unity3D server also plays a pivotal role in the application of this two-way information flow. It bilaterally receives building information from the data component and

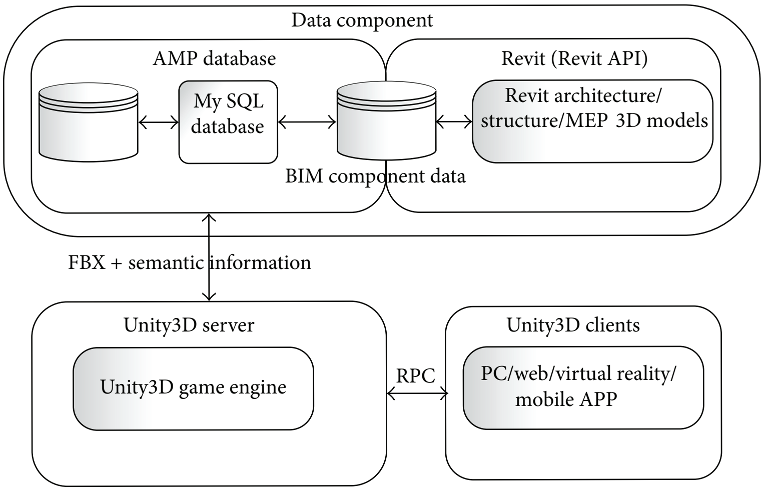


Figure 3: Three interconnected components of the BIM-VE.

the Unity clients, and concurrently generates the serious game environment for clients and enables updating of the building information in Revit according to the information flow in the data component. The Unity3D server consists of several component engines to create the adjustable virtual reality environment for fire emergency training and guidance. A graphic engine is critical in generating the graphical display on screen and providing the interface to load, manage, display, and animate the textured BIM components/data in the serious game. The main parts of the graphic engine are asset management, game object management, and terrain management. Asset management is responsible for the import and export of reusable game assets/packages such as shader, preferb, material, animation, and avatars. Game object management is responsible for creating new game objects with different shapes and adding particle systems, camera, GUI, light, wind, and so forth to the current scene of the serious game. Terrain management provides a handy tool to create terrain background and manage geomorphic high map effectively. The physics engine can simulate the mechanics of rigid-bodies, collisions, joints (building elements), or particle systems (smoke, fluids). Lastly, the audio engine provides the ability to generate realistic sound within the serious game.

The workflow of the application on the server side is shown in Figure 4. Although there are several activities using Unity3D's built-in library for synchronization, there are some activities that are not supported or not at the layer where the Unity3D game engine can interact with them. Therefore, when the server starts up, the first procedure to implement is to create an instance in the database to store this information. Next, it waits for the semantic information to load. The loading time varies depending on the amount of building information in the BIM model. The internal process of loading data is to convert Revit building format to FBX format. Then the FBX model is loaded into the Unity server's memory and converted into our custom format, which buffers at the network layer for incoming clients to load. Finally, it is loaded and rendered on the server screen. The processed data is then sent to clients and rendered on the client side. As the process is asynchronously in the time client loading environment, an administrator on the server side can begin to calculate evacuation routes according to the updated building information in the data component. To reflect the fire circumstance, the administrator in server can also set up fire, smoke, explosion, and dangerous areas at appropriate locations.

Figure 5 shows a generic activity flow on the client side. The client first needs to connect to the server by entering the server IP address, and then it waits for the semantic and geometric data. After that, the clients automatically update the virtual environment and services based on the received building information from admin.

4. BIM-VE for Fire Emergency Evacuation

4.1. Path Finding Algorithm and Space Representation in the BIM-VE. There are some factors that humans consider often but algorithms do not fully understand such as environment based movement and time from one point to another point. Therefore, the BIM-VE integrates informative graphs in the mathematical sense—path finding algorithms to generate the shortest path on a set of vertices with edge connections based on the updated building information [27]. Space search algorithms and search space representations are two key considerations when generating real-time evacuation routes according to changing building information in the BIM-VE [28–30].

Dijkstra's algorithm, best-first search, and A^* algorithm are three most common space search algorithms [27]. Dijkstra's algorithm works by adding all the closest not-yet-examined vertices into a representation graph from the object's starting point to the set of examined vertices. It expands outward from the starting point until reaching the goal, which is guaranteed to find a shortest path but works harder in performance and memory overhead. Conversely, the best-first search has a narrow scanning field but only

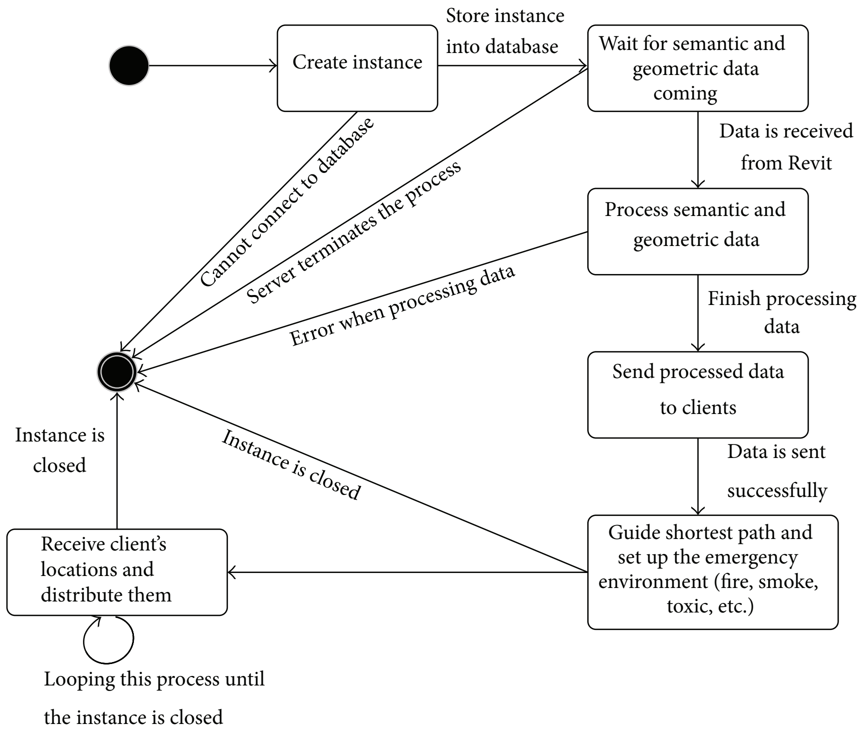


Figure 4: State diagram for administrator in server.

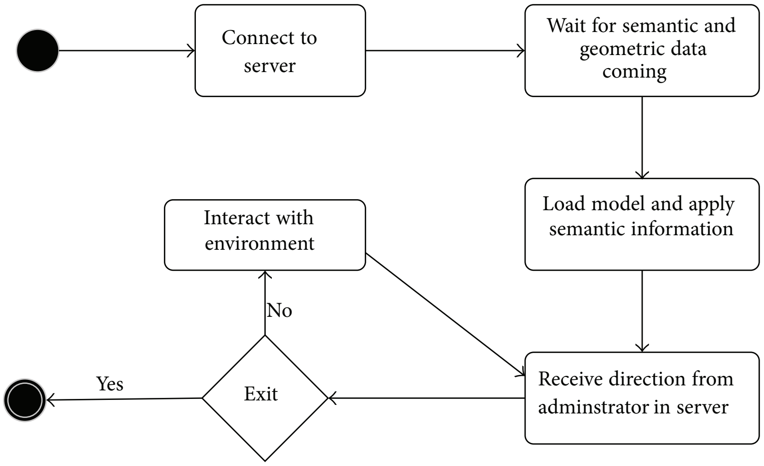


Figure 5: State diagram for clients.

considers the cost to the goal and ignores the cost of path so far, resulting in the path to goal becoming long, and tends to move forward to obstacles such as walls. The A* algorithm combines a heuristic approach like best-first search with formal approaches like Dijkstra's algorithm and has become the most popular choice for path finding problems and is fairly flexible in a wide range of contexts [27, 30], specifically, its knowledge-plus-heuristic cost function of notation x which is expressed as

$$f(x) = g(x) + h(x), \tag{1}$$

where $g(x)$ is the past path-cost function, known as the distance from the starting node to the current node x, and $h(x)$ is a future path-cost function, an admissible "heuristic estimate" of the distance from x to the goal. Therefore, the shortest path is to keep the least-cost path from start to finish.

The success of the A* algorithm in shortest path generation is that it integrates space search methodology of Dijkstra's algorithm [27, 30] (i.e., $g(x)$: higher search priority of vertices close to start point) to ensure the optimal path, with the information Best-First search explores (i.e., $h(x)$: favouring search vertices close to the goal) to decrease the space search area. The A* algorithm examines the vertex x

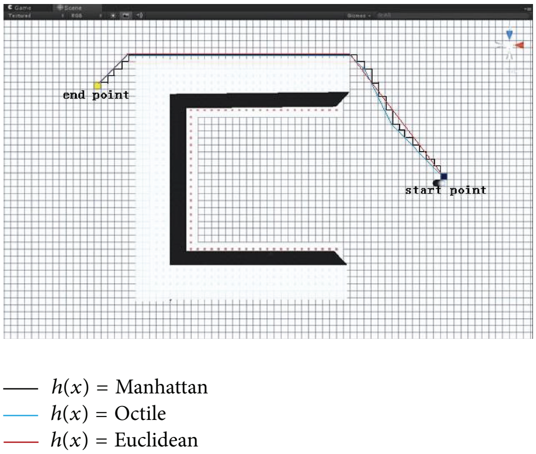


Figure 6: The shortest path generated by A* algorithm with different $h(x)$.

that has the lowest $f(x) = g(x) + h(x)$ each time through the main loop, balancing $g(x)$ and $h(x)$ to move from the start point to the end point.

In the world of space search algorithms, the heuristic of the A* algorithm must be admissible to guarantee an optimal path, meaning that the heuristic guess of the cost from x to the goal must never overestimate the true cost. However, the serious game often tremendously increases the calculation speed of the A* algorithm at the possible expense of a slightly suboptimal path by using an overestimated heuristic guess [27, 28]. For example, a larger overestimation of the heuristic guess speeds up the calculation of the A* algorithm substantially at the cost of an unnoticeable suboptimal path on a large open space with random obstacles such as columns or walls. Although the suitable overestimating heuristic can enhance space search speed of the A*, it does not mean that the underestimating heuristic is useless in the serious game. The underestimating heuristic can actually allow the A* algorithm to explore more nodes to get accurate and relevant search results in a complicated narrow space. Therefore, it is critical to decide what amount of overestimating or underestimating is required to balance the path optimization and calculation speed of the A* algorithm. The BIM-VE introduces the addition of a scale and selective $h(x)$ in a knowledge-plus-heuristic cost function to adjust the heuristic to suit the specific problem:

$$f(x) = g(x) + (h(x) \times \text{scale}), \tag{2}$$

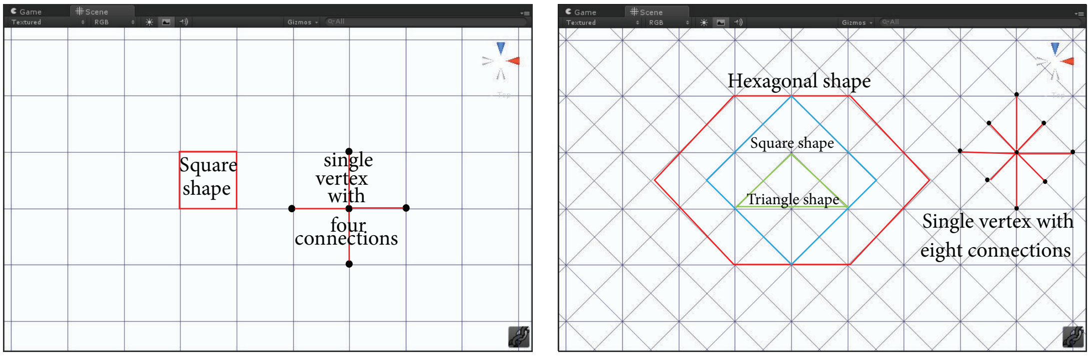
where $h(x) = |\Delta x| + |\Delta y|$ (i.e., Manhattan distance), or $h(x) = \max(|\Delta x|, |\Delta y|) + 0.41\ \min(|\Delta x|, |\Delta y|)$ (i.e., octile distance), or $h(x) = \sqrt{\Delta x^2 + \Delta y^2}$ (i.e., Euclidean distance), in which Δx is the value of distance change from current note x to the goal along x-axis and Δy is the value of distance change from current note x to the goal along y-axis.

If the scale is zero, the formula reduces to Dijkstra's algorithm: $f(x) = g(x)$, which can find the optimal path at the expense of search time, because it uniformly explores outward in all directions. If the scale is larger than 1, the behaviour of A* algorithm is toward the behaviour of best-first search algorithm, which cannot guarantee the optimal path but finds the goal as quickly as possible. As for heuristic selection, path finding on a grid has three selective heuristics; Manhattan distance, octile distance, and Euclidean distance. Specifically, Manhattan distance does not take diagonal movement into account, which would overestimate distance. The octile heuristic (also known as Manhattan diagonal distance) assumes that only 45° and 90° are permitted for the movement, which basically corresponds to movement in the world, because it provides the most precise heuristic to use on the squared grid of a video game and therefore is the default $h(x)$ in the BIM-VE. The Euclidean heuristic underestimates distances because it assumes the paths can take any angle but can work with a hexagonal grid to provide the most elaborate movement if necessary [27]. The BIM-VE adopting the knowledge-plus-heuristic cost function with different $h(x)$ to calculate the shortest path from start to finish is shown in Figure 6. The black line is the shortest path generated by A* path finding algorithm with Manhattan distance (i.e., $h(x)$ = Manhattan distance) and can only go following horizontal and vertical direction between neighbour grids; the blue path generated by A* algorithm with octile distance can move though diagonal directions between nearby grids; the red path generated by A* algorithm with Euclidean distance can head to any direction and connect any two grids if there is not any obstacle between them.

By altering the value of the scale and $h(x)$, it is possible to see how A* behaves to suit the problem, depending on the complexity of the virtual environment. For example, A* can take Euclidean distance with a relatively small scale adjustment to carry out path finding in a complicated building with narrow corridors and stairs, which can guarantee that A* algorithm can find the shortest path using dense nodes and arbitrary directions. Since the suitable scale and $h(x)$ have to be discovered experimentally, a user interface is provided to adjust their values in the Unity3D server to make A* path finding suitable to the building information in the BIM-VE.

Through the above illustrations, it is assumed that the space search algorithm is being used on a grid of some sort, where the "vertices" given to the algorithm are grid locations and the edges between the vertices are directions the shortest path could travel from a gird location. The algorithm though is only half of the picture. The space representation can make a distinct difference in the algorithm performance and shortest path quality [28, 29]. In general, the fewer vertices the space search algorithm explores, the faster it will be; the more closely the vertices match the positions that units will move to, the better the shortest path quality will be. Therefore, an appropriate space representation is required to fit into a BIM model and allow the 3D real-time path finding search in the BIM-VE [28, 29]. Generally, the three main groups of search space graphs are grid graphs, navmesh graphs, and point graphs [28, 29].

Navmesh graphs work based on triangles or polygons where each shape covers the walkable surfaces of the world. This generates very precise movement with blazing speed and low memory footprint as appropriate polygons can describe large areas with very few numbers. Similar to movement



(a) Higher path calculation but lower quality

(b) Lower path calculation but higher quality

Figure 7: Flexible node connections to represent common shapes used by grids.

within the grid system, the navmesh graph also provides tile, edge, vertices, or a combination for path movement. However, navmesh graphs normally work on fixed search space because ever-changing space information would put a huge strain on the memory footprint leading to the possibility of a crash [28–30]. Point graphs can be built by user-placed waypoints (or "beacons") that are linked to each other. They check the connections between waypoints to define a point of walkability. These graphs are customizable and flexible, and game designers can easily handle 3D game worlds by placing an array of points at any point in 3D space. However, they suffer from path complexity and path smooth problems because user-placed points are usually not optimized. Worse still, if the space information is changed, the user-placed points must be manually modified to avoid unrealistic path results [28–30].

It has been shown that an A^* algorithm working with a grid graph representation can quickly find the shortest path during runtime [31, 32]. Grid graphs represent the search space by subdividing the world into small regular shapes (i.e., tiles) and generate nodes on the shapes. Common shapes used by grids are triangular, square, and hexagonal [28–30]. The BIM-VE provides flexible connections (i.e., four or eight connections for a single vertex) to balance the shortest path calculation and quality to cover the common shapes that represent the world [32], which are shown in Figure 7. It can be seen from Figure 7(a) that a single vertex (the black dot) connects four neighbour vertices to form a square unit in the search space. It simplifies the search directions to four to get higher path calculation speed but loses path quality because the path cannot go diagonally. Figure 7(b) shows single vertex (the black dot) connecting eight neighbour vertices forming a hexagonal, square, or triangular shape to represent the space which allows the path to go diagonally, making the path quality higher at the cost of path calculation speed. Grid graphs can quickly provide reasonable shortest paths for most spaces and can respond to runtime changes of the world graph very well because of its adaptable common shape representations. However, it cannot address the world containing overlapping areas such as a 3D building with multiple floors [32].

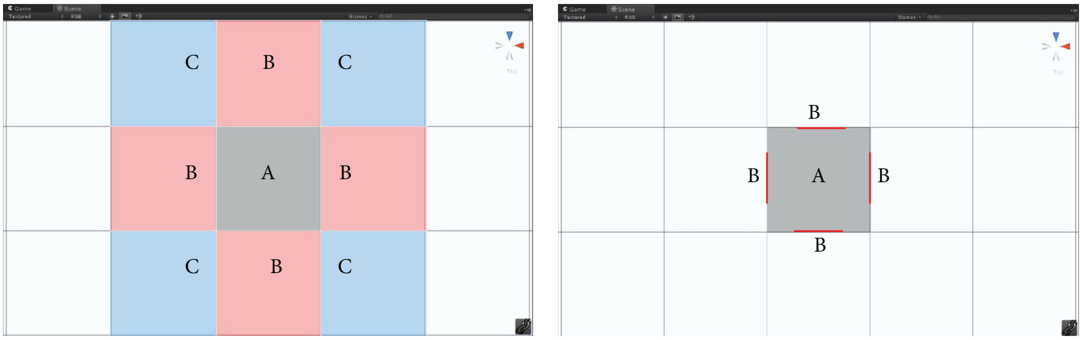
Within grid graphs, there is a choice of tiles, edges, and vertices for the shortest path movement [28, 29]. Tile movement is especially useful for the virtual environment in which units only move to the centre of a tile. In Figure 8(a), the unit at A can move to any B or diagonally to C with the same or higher movement cost. If units are not constrained to grids and can move anywhere in a grid space, or if the tiles are large, edge or vertex movement would be a better choice for finding the shortest path. Compared to unit moves from centre to centre, using edge movement, the unit will move from A to B directly through one edge to the other (i.e., red line in Figure 8(b)). Obstacle corners can usually be mapped with vertices of a grid system (i.e., square red dot in Figure 8(c)). With path finding on vertices, the unit moves around an obstacle from corner to corner, producing the least wasted movement. Therefore, movement on vertices is the default for shortest path finding in the BIM-VE.

4.2. The Implementation of Path Finding Algorithm for Evacuation Guides.

The limit of an A^* algorithm working with the grid system for the subject of fire evacuation is that the end-users in danger may be on different floors and want to effectively find the shortest evacuation route according to ever-changing emergency information. Thus, the BIM-VE proposed utilizes an adjustable A^* algorithm and layered grid graph to respond to a building emergency using the AMP database. The adopting workflow with main corresponding classes and methods is expressed in Figure 9.

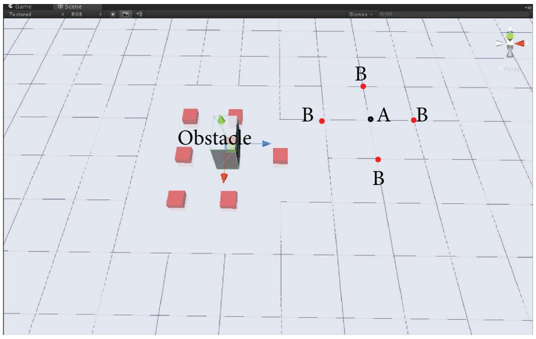
Specifically, during the stage of processing building information, the most important two classes for automated data transferral in the data component are "DataExtract" and "ServerInteraction." The "DataExtract" instance (objects) implements a process to read the current Revit model and write the information to FBX and semantic file. Because Revit contains all semantic information of the building design, we do not need to extract all of the information, only the useful information for fire evacuation. This useful information includes the following:

(i) object types: floor, wall, door, windows, fire alarm, marker, ceiling, roof, and obstacle,



(a) Tile movement

(b) Edge movement



(c) Vertices movement

Figure 8: The path movement within the grid system.

(ii) properties: unique ID, floor number of the object, height, volume, width, door status, and position marker ID number.

The "ReadSemantic" method declared in "DataExtract" class reads the property information and returns it to the "SendDataToServer" method. The "SendDataToServer" method then uses a HTTP protocol to send the results to the server and stores them in the AMP database.

The "ServerInteraction" object helps Revit interact with the Unity3D server to upload and download data. In order to interact with the server, it needs an http protocol interface that is implemented in the "HttpClient" variables of the class. The "FetchServerList" method declared in the "ServerInteraction" class downloads a list of available servers. In our current implementation, only one server can run on a machine at any one time; therefore, it always returns the single server running on the same machine. The results are stored into the "ServerIPList" and "HostList" variables (i.e., a unique ID of a server). When connecting from Revit to Unity3D server, the "SelectedServerIP" and "SelectHostID" variables are populated based on the connection, which also initialises the connection for the "HttpClient" variable.

On the other hand, "GSProcessing" and "SemanticInfo" are the most important classes which process semantic and geometric information in the AMP database. Notably, the "GSProcessing" object has several predefined variables that are critical to the BIM-VE's operation. This is because the third party library defined in the "fbxPlugin" variable to import the model is closed source. The standard size of the imported model is unknown, but the building needs to be scaled properly to allow the virtual agent to execute the path finding algorithm to pass through the open space. Therefore, the "buildingScale" variable defines the ratio size of rendering model comparing to the standard size of the imported model; the "buildingPos" variable defines the centre point of the building following the coordinates in the Unity3D Server to ensure that imported model will lay within the limits of the work area; the "HttpClient" variable defines the interaction of HTTP protocol (to download and upload data and check "SyncID" variables for synchronisation). Furthermore, the "SemanticInfo" object defines the structure of the semantic data: the "ID" variable is unique and is extracted form Revit. The "objName" variable stores the ID generated by Unity3D server for the imported object. "Type" stores the object type which is also extracted directly from Revit such as floor, wall, and door. The "pNames" and "pValues" variables store the arrays of properties extracted from Revit such as floor number, height, and volume.

In the "GSProcessing" class, the "semantics" array type is extracted at the beginning of the "ApplyingSemantics" method that is run after the "DownloadSemantic" method, which initiates a loop to check each 3D object and ID of building objects to find the appropriate "SemanticInfo" objects in the semantics array. The path finding rules will then be applied to calculate evacuation routes during the create-evacuation-path stage. For example, the A* path finding algorithm calculates the shortest evacuation path only based

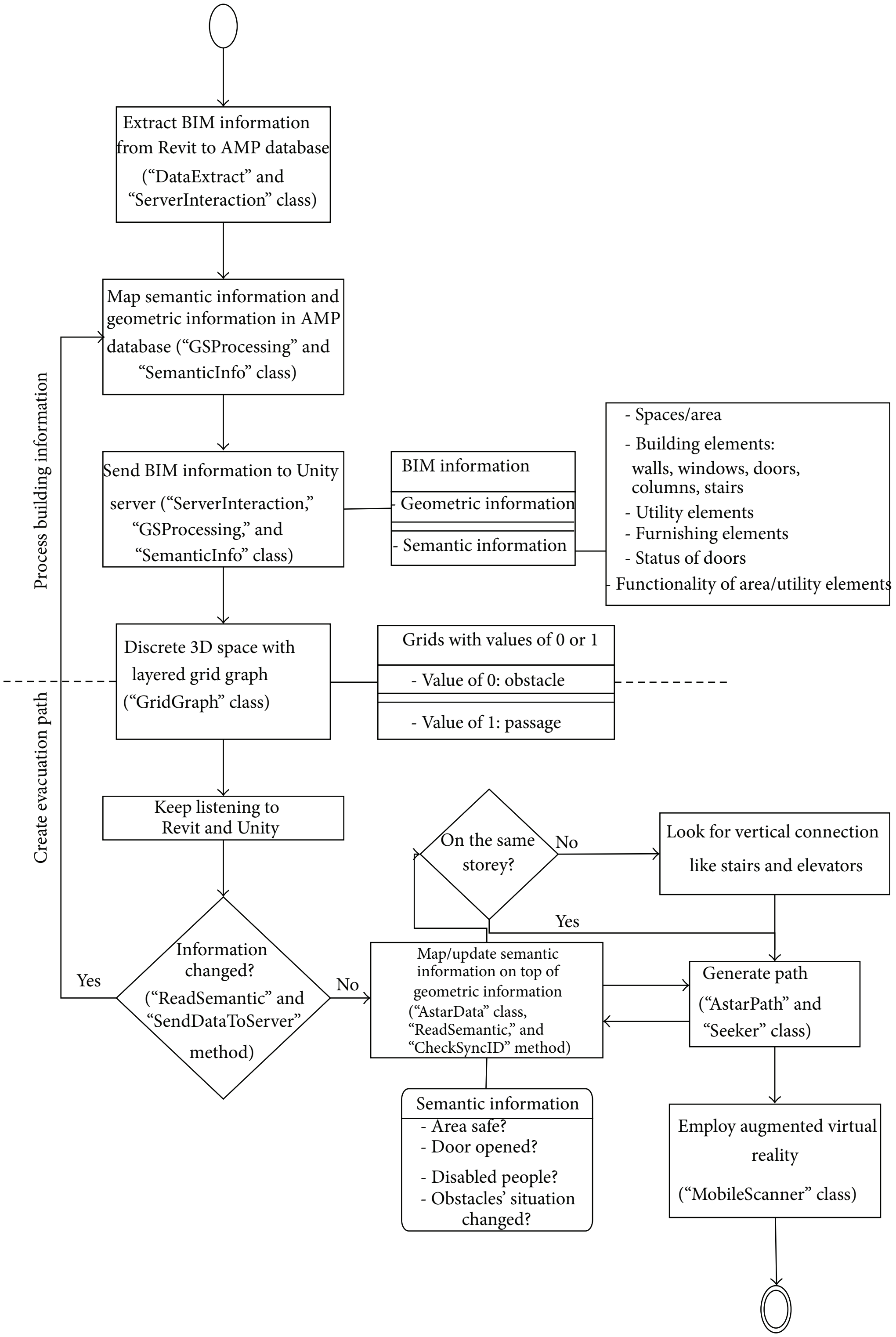
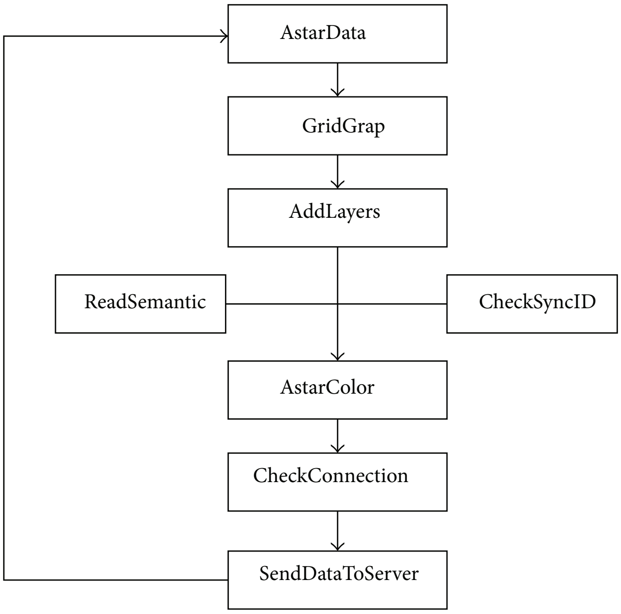


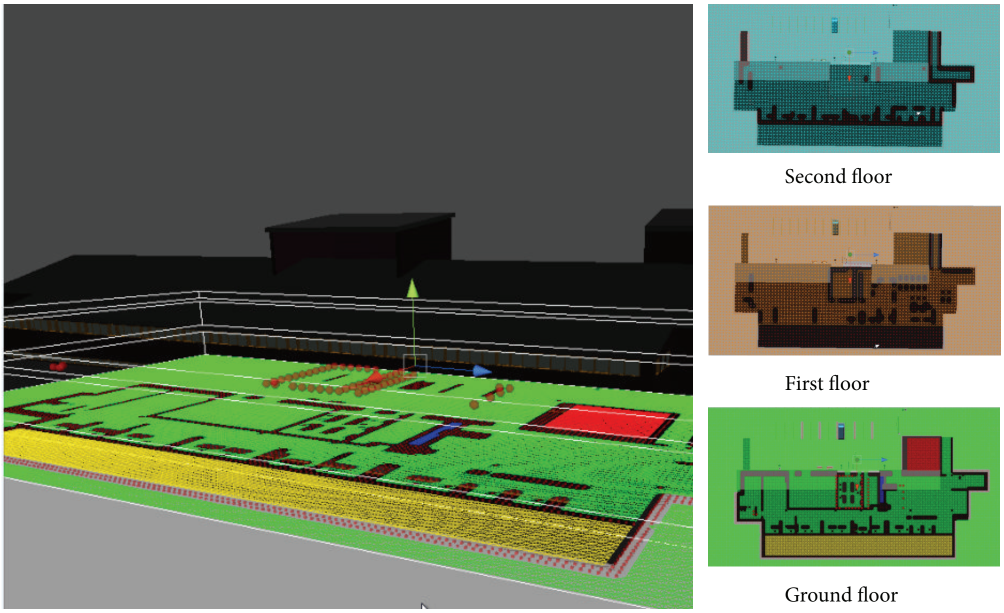
Figure 9: The workflow with associated classes and methods for the implementation of the path finding algorithm in the BIM-VE.

on the walkable objects (e.g., floors (without fire), (opened) doors, and (cleared) stairs) rather than unworkable objects (walls, (closed) doors, and obstacles (such as fires and dangerous areas)).

The A* algorithm with adjustable heuristic is distinct in this instance due to its ability to work with a layered grid graph to provide dynamic path finding within a 3D space; it checks whether the defined start and end points are on the



(a) The flowchart for “AstarData” class



(b) Layered grid of nodes and marked obstacles

Figure 10: The flowchart for “AstarData” class working with its associated methods to generate and update discretized space.

same layer (i.e., floor) and adjusts the heuristic to ensure that the evacuation route proposed passes through walkable areas using the building semantic information. When creating shortest evacuation path, the classes that are used most in the algorithm are “AstarData,” “AstarPath,” and “Seeker.”

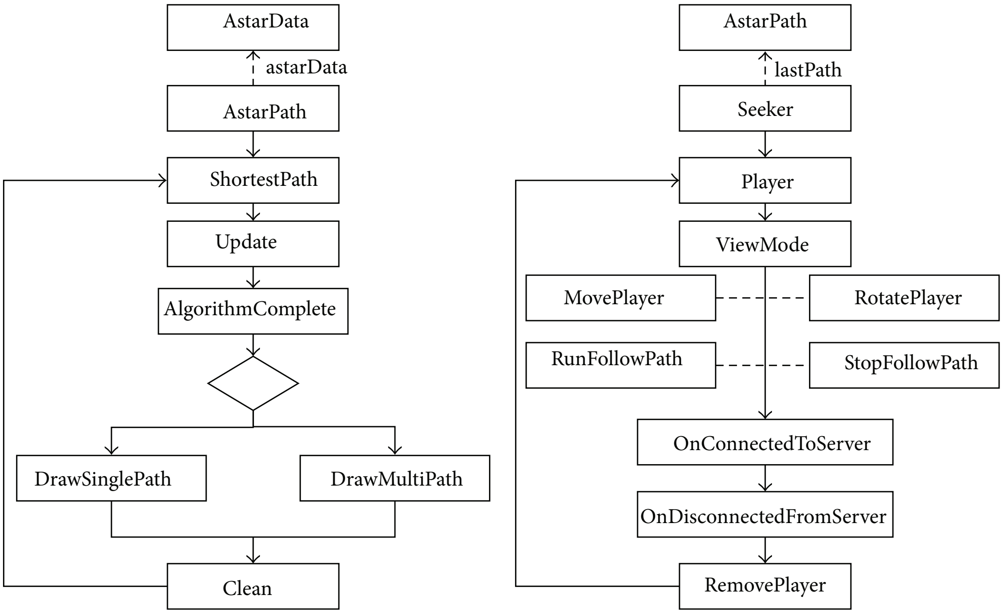
During the create-evacuation-path stage (Figure 9), the “AstarData” class and associated methods work to generate and update the discretized space (workflow shown in Figure 10(a)). Specifically, the “AstarData” object stores the grid graph with the semantic information, with the instance allocated to “AstarPath.astarData” to allow access to the layered semantic grid graphs with marked obstacles. The grid generator (“GridGraph” class) in the Unity3D server generates a layered grid of nodes via the “AddLayers” method. Then, it uses “ReadSemantic” method to map the building objects and spaces with their semantic information stored in “AstarData” and marks obstacles/dangerous areas and walkable areas with different colours by “AstarColor” method. By looking for vertical connections (judged by their semantic information) such as stairs and elevators, the grid nodes that are the nearest to vertical connections in different floors are connected in z-axis. Then, the BIM-VE checks if layered grid nodes are connected to their neighbours and automatically links connected nodes by employing the "CheckConnection" method to create preliminary layered and coloured 3D discretized space for the shortest evacuation path. Figure 10(b) demonstrates how grids of nodes are layered and marked for obstacles in the multifloor building. The BIM-VE marked green, brown, or blue grids of nodes for walkable area on different floors (i.e., on ground and the first and second floor separately), red nodes for obstacles, and yellow grids of nodes for closed spaces. In addition, the Unity3D server keeps checking whether the building information collected from Revit via the database and the server itself has changed, via the "ReadSemantic" and "SendDataToServer" methods, and if necessary updates the layered grid graph to create the updated discretized space at fixed time intervals. Specifically, the "SyncID" variable and "CheckSyncID" method are created to work with the "ReadSemantic" method to check if the semantic information has changed, which is critical in synchronising building information between Revit and Unity server. Herein, the semantic information flow can be used as referenced information to synchronize geometric building information between Revit and the Unity3D server. For example, doors can utilize their semantic status (i.e., open or closed) to change their geometric position to connect or block evacuation paths. Walls can be shown or disappear according to their semantic indication such as normal or broken. The checked building information in the BIM-VE includes geometric information such as dimensions of building components and semantic information such as safety of area, status of doors, materials of walls, and functionality of utilities.

The "AstarPath" class is a singleton class (i.e., only one active instance of it in the scene), which calculates evacuation routes based on information in "AstarData," and often collaborates with the "Seeker" class that manages the path calls and path smooth for a single object in the existing A^* shortest path library. "ShortestPath" and "Player" are the leading derived classes inherit from "AstarPath" class and "Seeker" class separately but add more attributes related to where, when, and how.

The "ShortestPath" class is responsible for calling the existing A^* shortest path library and putting the path finding rules on the updated layered 3D discretized space in the Unity3D server and clients through the "pathAlgorithm" interface (that is also supported by the "Seeker" object). It works with associated methods to generate real-time fire evacuation routes (Figure 11(a)). There are several important variables for "ShortestPath" to generate the evacuation path. In particular, the "lastPath" variable is a set of ordered vectors storing the latest shortest path for the server and connected clients. The "lastPoints" stores the latest points constituting the shortest path. The "pathMode" variable indicates if the current application running is single path (one start and end point) or multiple paths (one start and multiple end points). As mentioned, there are also critical methods to get and update the shortest evacuation path in the BIM-VE. The "Update" method continuously runs to construct the shortest path. When it detects that there are enough points to construct the shortest path, it will use the "pathAlgorithm" interface to run the algorithm and return the result to "AlgorithmComplete" (a callback method). The results will be stored in "lastPath" to update the current path. After synchronising the results with connected Unity3D clients, the "DrawSinglePath" or "DrawMultiPath" method (depending on "pathMode") will draw the evacuation routes. Finally, the "Clean" method clears all the "lastPoints" and the "lastPaths" variables so that the new path can be generated.

The "Player" object is an agent to visually follow the "ShortestPath" object results, with a float value used to adjust its movement speed (Figure 11(b)). The "playerObjectID" variable stores the ID of the character being controlled by the users via Unity3D clients in the serious game. The "playerStatus" variable indicates the current movement status of the player: standing, walking, running, and so forth. The status is checked during the "Update" method and issues appropriate actions to the virtual characters. There are two "ViewMode" options available for the player to switch between; these are "freeView" and "firstPersonView." If end-users choose the "firstPersonView," the "MovePlayer" and "RotatePlayer" method allow end-users to use different input devices to freely control the current character and also synchronise latest movements with all other machines. Thus, the players in the Unity3D server and different clients can see the movement of each other for evacuation guidance and training. In both "ViewMode" options, "RunFollowPath" and "StopFollowPath" methods can make the character move along or stop following the shortest path if there is one, which allows them to enhance their holistic understanding of the evacuation process. The "OnConnectedToServer" method runs several initial functions to synchronise the planned shortest path between the server and clients. It also helps load the semantic models for connected clients. "OnDisconnectedFromServer" is a method that deletes the current user on all machines by using a "RemovePlayer" method if a disconnection occurs.

Lastly, the BIM-VE can further utilize augmented visualization technology to mix the virtual and real worlds when the building design is constructed. This allows general end-users to get more effective and accurate evacuation guidance and training on their mobile devices. This application currently supports Android, iOS, Blackberry, and Windows phones, meaning that nearly all smart phones and tablets with a camera can be utilised. The augmented plugin Metaio is integrated within the proposed system and is able to recognize the artificial markers to map end-users' positions between the virtual and the real. Specifically, the "MobileScanner" class implements the metaio SDK on mobile devices, which helps end-users use their mobile device camera to identify the position marker in the real world and map their locations in the virtual environment. The library from the metaio SDK conducts pattern recognition on the captured image, and, when a pattern is recognised, it converts it into an integer number called "markerID." Metaio predefines 255 different patterns and each is linked with a unique "markerID" (from 1 to 255). A "markerID" is linked with a location that is specified by semantic data in the "GSProcessing" class. When an object is detected as a "markerID" object, the system records the coordinate and the "markerID" number.



(a) The flowchart for "AstarPath" class

(b) The flowchart for "Seeker" class

Figure 11: "AstarPath" class and "Seeker" class working with their associated methods to generate the shortest evacuation path and virtually follow the path.

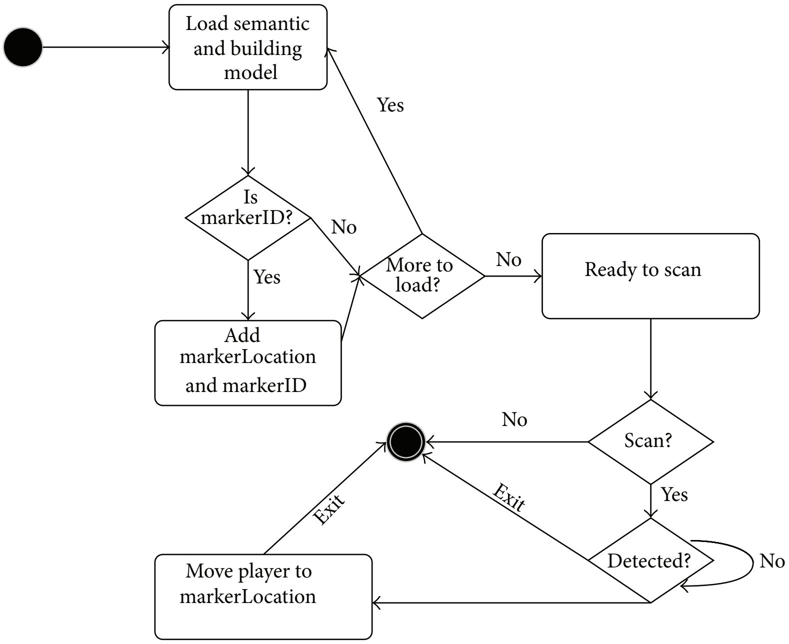


Figure 12: Scanning pattern on mobile devices.

Figure 12 illustrates the work flow used for locating position of the user. On application running, the "Start" method initialises the scanning process by reading a configuration file defined in metaio SDK. It then constructs empty "markerLocations" and "markerID" variables. Following this, the "Update" function continuously runs on each frame and firstly checks the camera status (i.e., turn on or turn off), and then "ScanningMarker" is called from the "Update" method to begin scanning when the camera is turned on. The "CallbackScanner" is automatically called when position markers are recognised. It works with Unity3D's built-in "getComponent" variable to get and move a player to the location of the detected "markerID" objects.

When a marker is recognized in the real world, the position of the end-users will be found in the BIM-VE. Then, the evacuation routes would use the positions of end-users as the start point to offer each end-user an intuitive evacuation guide in both a 2D minimap and a 3D model. The

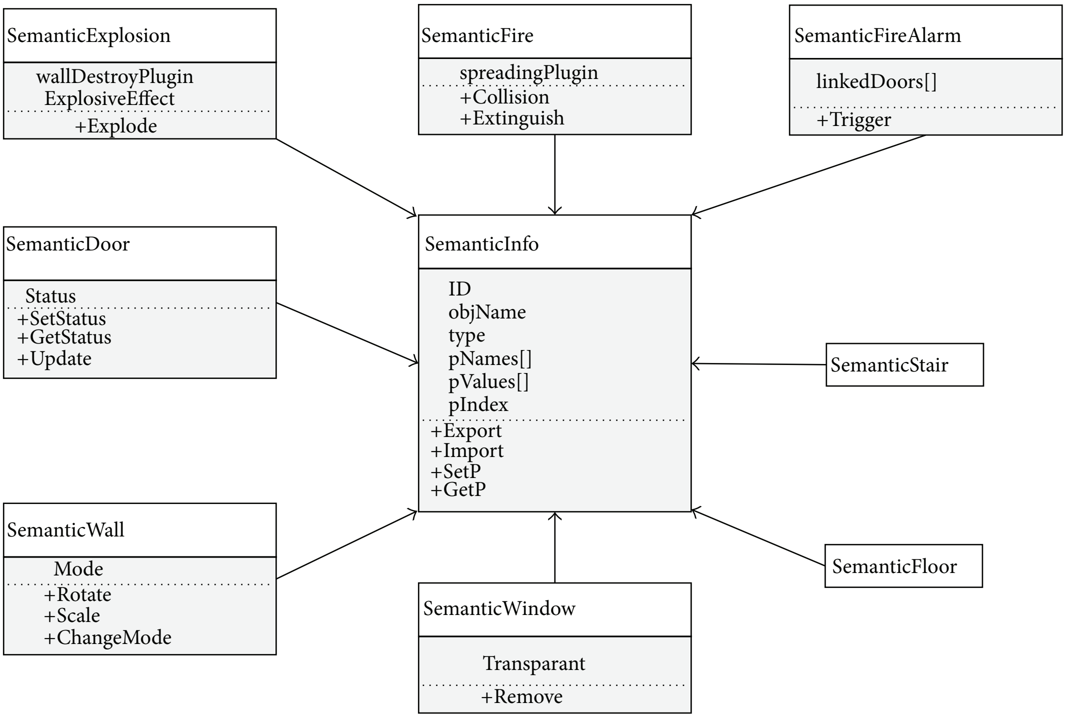


Figure 13: Interactive diagram between classes for dynamic emergency scenarios generation.

minimap gives an overview of the building layout and helps the user keep track of current location. In a building with multiple floors, the minimap shows the current floor map and automatically switches when the player moves to another floor. Currently, the function based on the "MiniMap" class is still limited because several important variables need manual setup, such as the textures' array to store the image of the map for each floor, and "centerPoint" to reference the 3D space centre into 2D image. The "3DToMinimap" and "minimapTo3D" are used to convert coordinates between the 3D environment and the 2D map, which keeps the positions of players in 3D space consistent with their positions on the 2D map. The "GetCurrentFloor" method is based on the player position to calculate the current floor where the player is on, and then "DrawMap" method displays the appropriate 2D map on the screen.

The BIM-VE provides end-users two modes for the evacuation service: the single-path evacuation mode and the multiple-path mode. The single-path mode helps end-users using Unity3D clients to find the recommended evacuation path from their position (recognized by position markers) to the safest point (defined by server, e.g., the nearest exit or fire rally point). In practice, evacuation paths are not unique, so the end-user using a Unity3D client can choose the multiple-path mode to find evacuation paths to all available exits. The multiple-path mode is especially useful for end-users with a disability who might be unable to follow the recommended evacuation path due to impairments such as movement limits (i.e., not easy to climb stairs or quickly pass through dangerous areas). By recognizing dangerous areas and circulation points that are not suitable for a person with a disability, these end-users can find the evacuation path that might not be the shortest but is the safest.

4.3. Dynamic Emergency Scenarios for Evacuation Training and Research. The application of the adjusted path finding algorithm on 3D layered discretized space can respond to the emergency environment of a building with multiple floors in real time and mix virtual and real environments to provide updated evacuation guidance on mobile devices. However, when it works with virtual reality equipment (introduced in Section 3.1) for emergency evacuation training and research, it is necessary to introduce a library approach that works with semantic building information to create dynamic fire scenarios in the Unity3D server/clients, so participants within the virtual experiment stay focused and cannot anticipate scenarios increasing reliability of experimental results.

The library approach, where standard emergency components can be archived for reuse to create unexpected events, can not only eliminate the time wasted in repetitive data translation and optimization of rendering parts, but also add semantic information and animations to enhance the performance of the serious game. Coupled with the two-way information channel, the building information can be automatically translated into the virtual environment. However, this kind of translation does not include the definition of factors influencing fire response performance. Therefore, the library approach works on top of the bidirectional information flow to dynamically generate emergency scenarios to enhance participant's understanding of the evacuation process. Current library functions include setting up player spawn points, adding fire/toxic/smoke, display of people, running unexpected events such as explosions or wall collapses, and activating fire alarms with lights and noise. Semantic information extracted from BIM model is utilised to enhance performance of evacuation training, employing the interactive class diagram depicted in Figure 13. The "SemanticInfo" object contains the general properties of a semantic object. Working with it, specific class objects contain some special properties for handling wall collapse, automatic-shut fire doors, fire alarm activation, expanded fire, and window break events. Note that "SemanticStair" and "SemanticFloor" objects have their own class but are empty as their semantic information is currently under development for fire propagation. The "SemanticFire" object is the representation for fire, smoke, and toxic gas, which have similar properties, so it is possible to group them into one to simplify the system.

The built-in physics engine in Unity3D server is the main component to simulate the dynamic physical interaction between objects on the basis of the laws of physics such as gravity and collision. To be able to run the simulation in real time, it is inevitable that the physic performance will be simplified, because entirely correct physics calculations are not necessary and only need to "look realistic" during the evacuation training. The simulation in the evacuation training is based on the physics of rigid bodies (rigid body mechanics of objects), elastic bodies (soft body dynamics of fabrics or cloth), and object collisions (collisions between obstacles and characters). The built-in particle system simulates fire, smoke, and explosions, along with extracted material properties (semantic information) from the BIM model associated with the geometric information to simulate variable speed and dynamic fire propagation. The structural elements are split down into a finite number of smaller parts to simulate collapse events caused by explosions. Joints with up to six degrees of freedom on character bodies can be mapped with the tracking information of motion sensors to immerse participants into the 3D virtual reality environment (as described in Section 3.1).

The process to carry out fire evacuation training and research within the dynamic fire scenarios is as follows.

(i) The administrator within Unity3D server creates a host/session that holds building information for evacuation training and research. The two-way information channel then transfers both semantic information and geometric building information from the BIM to the serious game.

(ii) Unity3D server then loads the appropriate emergency components with behaviour scripts through the inventory library, which works with building semantic information to create unexpected virtual fire scenarios.

(iii) Unity3D then synchronizes fire scenarios with the Unity3D clients for evacuation training and research in the specific building.

(iv) Before virtual experiments, participants fill in a questionnaire about their personal information and physical condition that might influence human fire response.

(v) The administrator introduces the building layout and how to use the BIM-VE in the virtual reality environment. The participants are told that they can quit the experiments at any time if they feel uncomfortable.

(vi) The avatars representing participants are placed at the start point in the serious game. Based on the chosen level of participants' game experience, the suitable control version (five versions in total: desktop first person mode, desktop flight mode, 3D projector with Razer Hydra joystick, and table version) will be loaded.

(vii) Allow participants to walk through the building in the BIM-VE, to familiarise themselves with controls and functions. Inform participants that they may communicate with other virtual characters and that environmental factors can kill their character during the evacuation.

(viii) Restart the avatars at another spawn location. Perceived risks are gradually shown, which include people's crying, fire noise, gradual increase in fire/smoke, and other virtual characters who begin to evacuate as a group or individually.

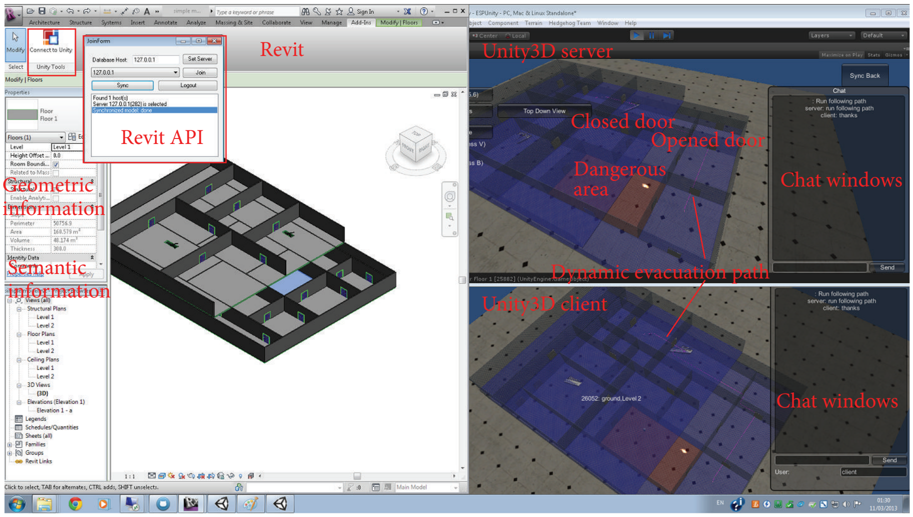
(ix) The administrator in Unity server then adds unexpected events such as fire and explosion to push participants to respond to the fire environment and perform the evacuation process. Additional objects like fire extinguishers are also provided to finish specific tasks for evacuation research. After finishing the evacuation process, the administrator will show specific character avatars with evacuation AI (based on the implementation of adjusted path finding algorithm on 3D layered discretized space) to simulate the efficient evacuation process. Then, the participants follow the specific avatars to carry out the evacuation, which can train their behaviour and enhance their understanding about the evacuation process.

(x) Lastly, a questionnaire is completed (after evacuation training) to investigate the factors that are hard to analyse through visual recording of the evacuation. The feeling and suggestion of participants are also considered.

The system keeps track of the evacuation behaviour by video recording. These recorded videos are utilized to qualitatively and quantitatively analyse the human fire response performance, in conjunction with the qualitative questionnaires at both the start and the finish.

5. System Testing and Evaluation

The system testing includes (1) the prototype functionality of the two-way information channel and its applications on the evacuation guidance and training, (2) the integration of virtual reality hardware and software through middleware, (3) the accuracy of evacuation simulations according to



Found 1 host(s)
Server 127.0.0.1(282) is selected
Synchronized model done

: Run following path
server: run following path
client: thanks

Figure 14: Dynamic path finding based on building information parametric in the BIM model.

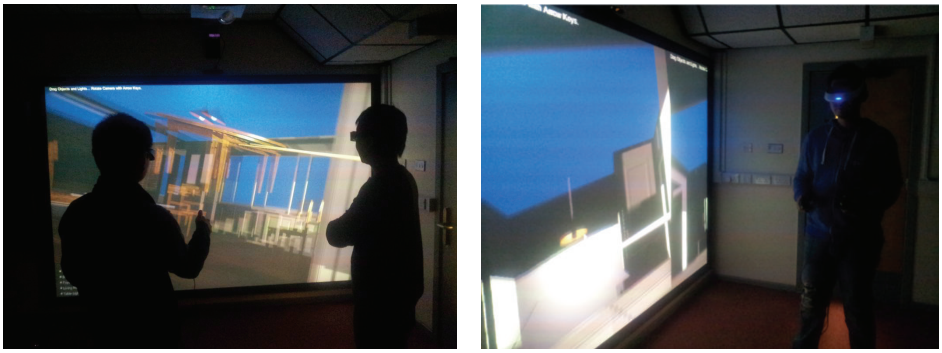
the requirements of the end-users and the ever-changing building information during a fire emergency, and (4) the effectiveness of dynamic changes of geometric and semantic building information to keep participants focused on the virtual emergency drill.

5.1. Scenario Based Dynamic Path Finding Test. The parametric nature of BIM plays a key role in rapid and accurate emergency management activities, such as real-time evacuation path guidance. However, most traditional path finding simulations for fire emergency evacuation work only in 2D space and find it difficult to respond to the ever-changing emergency circumstances due to their limitations in utilizing real-time building information. Through the two-way information flow, the adjustable path finding algorithm in conjunction with the informative layered grid graph has shown it can provide a dynamic path finding simulation in the 3D space according to the updated building information from the BIM model and the Unity3D server. The most important factors considered to influence path finding results included the building geometric layout, the door status (i.e., open or closed), the status of area (i.e., safe or dangerous), and the character status (i.e., disabled or ordinary). Figure 14 demonstrates the dynamic path finding results based on the parametric settings of the building information in the property windows of Revit and emergency situations settings in the Unity3D server. The path finding simulation in the BIM-VE can be dynamically updated to respond to the real-time changes of the building information from both Revit and the Unity3D server and can be synchronized immediately between the Unity3D server and clients to provide accurate and timely fire evacuation guidance to the general end-users.

With virtual reality technology (supported by VR hardware and software), the fire evacuation path simulation can enhance the end-users' understanding of the evacuation process and make them get accustomed to the building environment and prepare them for an evacuation during a real fire disaster. Because the BIM-VE can work on multiple platforms, it is possible to engage a wide range of end-users to experience the evacuation process from an individual point of view, while walking around or through the evacuation design in different Unity3D clients (Figure 15). The virtual reality devices such as active 3D projectors, head mounted display (HMD) and Kinect for windows can immerse the local participants into the virtual fire drill to drastically improve their perception of the fire evacuation experience, than is achievable by traditional visualization methods. The local participants can further use these VR output and input devices to interact with the virtual building information model to complete specific tasks during virtual drills to deepen their understanding of the correct evacuation behaviour. In addition, network based Unity clients can support many different types of devices such as generic PCs and laptops and even web-browser based interfaces can easily connect large numbers of remote participants around the world at the same time to further enhance the service range of the fire emergency training/guidance or the research accuracy of the human fire response behaviour.

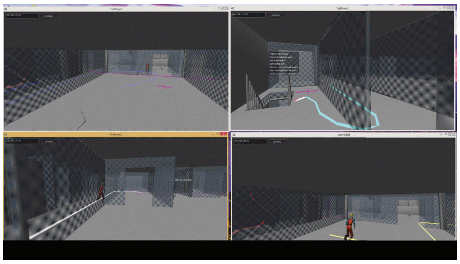
5.2. Evacuation Scenario Utilizing Mobile Devices Testing. The Unity3D clients of the BIM-VE support various commonly available mobile devices such as smart phones and tablets (using iOS or Android) equipped with a touch screen and built-in camera to provide the general end-user additional options for evacuation training and guidance throughout the building life cycle. It is commonly recognized that the unfamiliarity with a new or complicated building will delay the evacuation process because the evacuee is confused about how best to get out of the building during an emergency situation. The BIM-VE can transfer the building information model to the serious game for different purposes within a minute, which offers a huge potential for evacuation training during the building design stage and the evacuation guidance when the building is constructed.

The west building of Cardiff University's School of Engineering was used to carry out the evacuation testing on

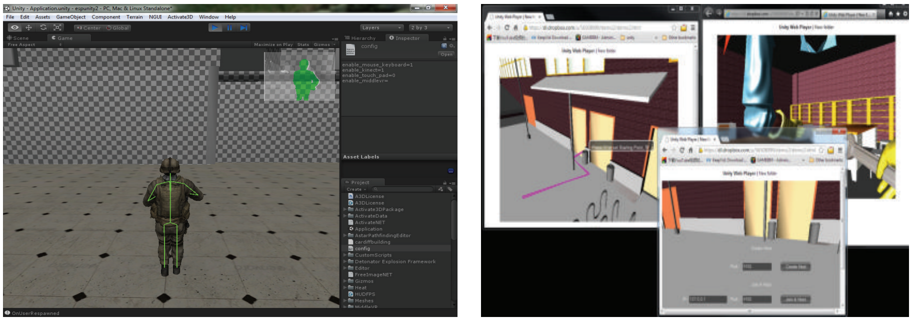


Public activated 3D view

Personal HMD (head mounted display) view



PC and Mac view



Kinect motion tracker view

Web-browser view

Figure 15: The 3D evacuation training on different platforms.

mobile devices because the layout of the School of Engineering is complicated and often causes confusion for visitors. Several participants who are not familiar with the layout of the building were invited to attend the testing. Firstly, they were directed to walk around the engineering school to obtain the basic building information. During the wandering, they were informed of the start location (i.e., the original position to begin the testing) and the end point of the evacuation testing (i.e., an emergency exit). Then, the participants are separately guided to the evacuation start point via a route that is different from the evacuation path and required to reach the end point without assistance of mobile devices as fast as possible. It was frequently noticed that some of them became lost during the evacuation or chose the longer route to the end point. Before the second round of testing, the basic functions of the BIM-VE on mobile devices were introduced in 3D virtual space and a corresponding 2D map, to the test participants. Then, the start point and end point of evacuation test were changed (keeping the same travelling distance) in case the participants anticipated the evacuation scenario. Similar to the first round of the testing, the participants were required to evacuate from the start point to the end-point, but they moved with the support of mobile devices running the BIM-VE (Figure 16). The evacuation time with or without mobile devices is shown in Figure 17 (the results for the participants who were lost or gave up during the evacuation were not included).

It should be noticed that the position markers that are set in Revit can help the end-users to map their positions in the real building with the 2D and 3D virtual environment during the evacuation. The BIM-VE also has other designed functions to help participants efficiently follow the recommended evacuation path generated by server such as setting current location as the begin point for the evacuation (i.e., blue evacuation route in Figure 16). The position markers with their semantic ID were mostly located on corridor junctions or places that might confuse the evacuees when trying to find the shortest evacuation routes (Figure 18(a)).

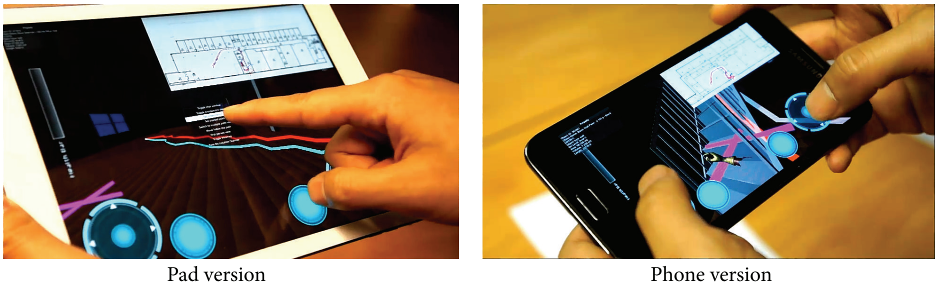

Pad version Phone version

Figure 16: Mobile application for general end-users to carry out effective evacuation.

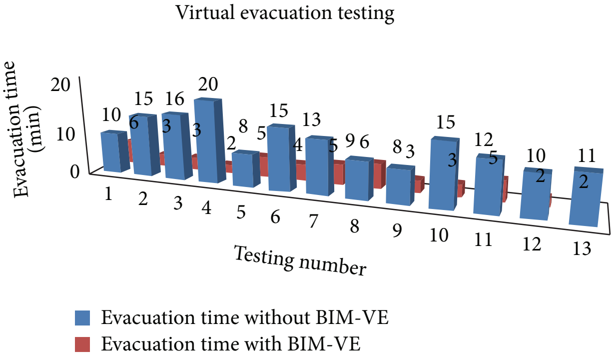


Figure 17: Evacuation time of virtual evacuation testing with or without mobile devices.

In tests utilising iPhone5s, iPads, and Android phones, the marker pattern can be recognised at a distance of around 3-4 meters in normal lighting conditions and the participants position is computed in under 0.5 seconds (Figure 18(b)). The average evacuation time with assistance from mobile devices was 3.8 minutes, which provide evidence that the BIM-VE operated on mobile devices can help participants significantly decrease the time taken to evacuate the building, although its application during a real emergency situation has to be tested further.

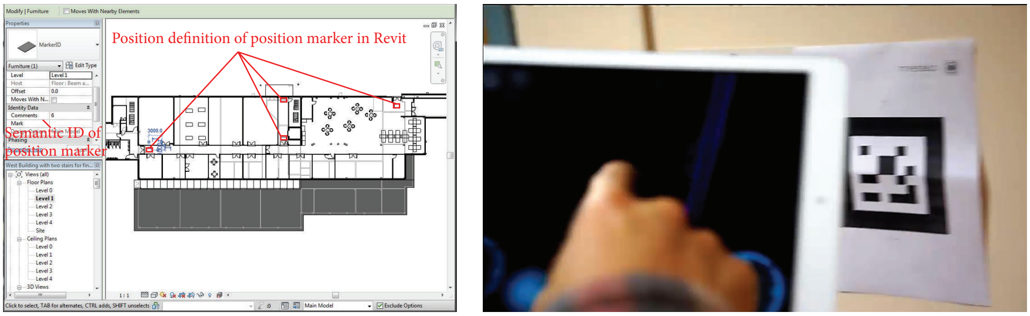
5.3. Dynamic Emergency Scenario Generation Testing. It has previously been introduced that the BIM-VE has the ability to keep participants of virtual evacuation training or human behavioral research by creating dynamic scenarios, generated by using a library based approach of building semantic information. The effect and tool library incorporated into the Unity3D server are shown in Figure 19, with the objective of increasing realism of the virtual fire disaster and eliminating any anticipation of the fire emergency scenario.

The effect library was utilized by the administrator of the Unity3D server to create unexpected events based on fire, smoke, explosion, and alarm warnings to test the participants' responses through the Unity clients during a virtual fire evacuation. These unexpected events work with building semantic information to create a vivid and dynamic building fire scenario. Take for example the fire effect on the library; it was added to the evacuation scenario in the Unity3D server with a specific time interval to create the dynamic spread of fire for the Unity3D clients. The fire spread speed is based on the building semantic information such as wall and floor's material and references to the fire engineering manual. In terms of the fire alarm, its semantic information in Revit is referenced to object IDs of fire-proof door, which control whether fire-proof doors are shut when the corresponding fire alarm is activated in fire evacuation scenario of the BIM-VE. The modification of evacuation path scenario with the semantic information of the activated fire alarm is described in Figure 20. When the spreading fire/smoke/toxic enters the detectable range of a fire alarm in the BIM-VE, the fire alarm becomes active with visual and auditory signals and shuts the referenced fire-proof door to prevent the spread of the fire while the shortest evacuation path in the Unity3D server is automatically modified and synchronized with the Unity3D clients to provide the end-users with the up-to-date evacuation training/guidance (Figure 21).

The tool library controlled by the Unity3D server aims to dynamically change the building layout and provide the participants of the Unity3D clients with specific fire-fighting equipment such as fire extinguishers to complete specific tasks. The tasks aim to explore human fire response and performance, which are mainly related to three factors: the nature of fire, the nature of the human, and the characteristics of the building. This component is still under development and will be discussed further in a following paper.

6. Conclusion and Future Work

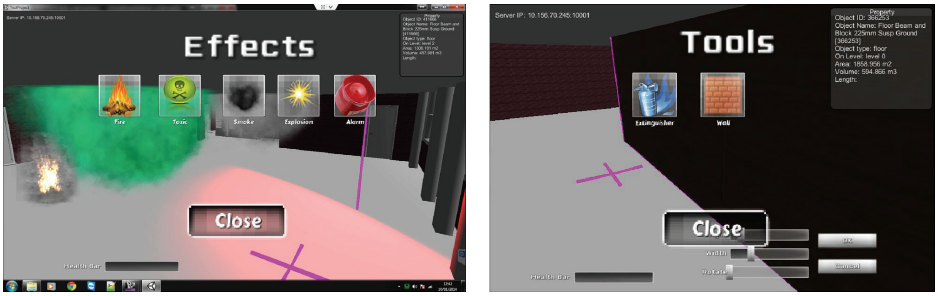
This paper introduces a BIM based virtual environment (BIM-VE) aiming at improving building emergency management. The research focuses on two key factors for emergency management: (1) timely two-way information flow and its



(a) Position markers with their semantic ID set in Revit

(b) A real position marker in testing

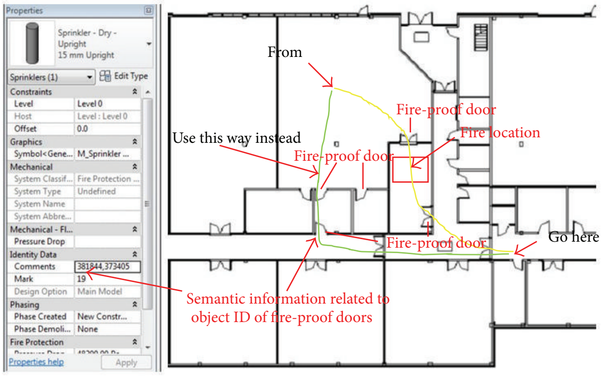
Figure 18: The position marker in the virtual environment and real building to help the end-users locate their position to effectively find the shortest evacuation path.



Server IP: 10.156.70.245:10001

Property
Object ID: 366253
Object Name: Floor Beam and Block 225mm Susp Ground [366253]
Object type: floor
On Level: level 0
Area: 1858.956 m2
Volume: 594.866 m3
Length:

Figure 19: Effect and tool library to create dynamic scenarios in Unity server.



Level: Level 0
Host: Level : Level 0
Offset: 0.0
Symbol<Gene...: M_Sprinkler ...
System Classif...: Fire Protection ...
System Type: Undefined
System Name:
System Abbre...:
Pressure Drop:
Comments: 381844,373405
Mark: 19
Design Option: Main Model
Phase Created: New Constr...
Phase Demoli...: None

Figure 20: The scenario of the fire alarm works with semantic information to automatically change the fire evacuation path ((1) and (2) are fire-proof doors whose IDs are 381844 and 373405 and referenced to the fire alarm/sprinkler; yellow route is original evacuation path and the green route is the alternative path when fire alarm is activated).

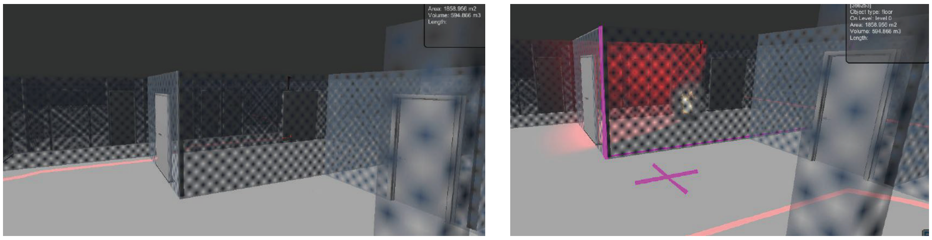


Figure 21: The automatic modification of evacuation path in the BIM-VE when the fire triggered the fire alarm that is referenced to fire-proof doors.

applications during the emergency and (2) convenient and simple way to increase evacuation awareness.

By utilizing the comprehensive data resources hosted in BIM, mobile devices held by building users/visitors, coupled with the help of specific tags, a real-time two-way and dynamic information flow has been successfully created and demonstrated between the virtual environment (provided by BIM and a game engine) and a real building user. The BIM-VE can create real-time evacuation routes according to the real-time location of the user.

Another research target was to provide convenient training (to building users) to increase emergency awareness. The tested scenarios have also successfully demonstrated the capability (of the developed system) to train building users, allowing them to quickly get familiar with the building and identify the right evacuation route.

The innovation lies on the seamless integration between BIM and the serious game, the semantic based smart path finding algorithm, and the leveraging of state-of-the-art technologies in practical problem solving. The system has been created and functionality has been tested; the next step is to validate its usability and actual effectiveness. A larger scale building user test is currently ongoing, and the results will be reported in further published works. In addition to this, dynamic emergency scenario generation can also be utilized to enhance reliability and validity of human fire response research; supporting virtual experiments and results are under development for further publications.

Currently, the BIM-VE works with Revit and a specific data format (e.g., FBX) to transfer building information from BIM to game, which limits its proliferation to work with other BIM software packages. As IFC (industry foundation classes) has been promoted as the de facto standard for data and process interoperability in the AEC (architecture engineering and construction) industry, one of our future works is to implement IFC interface instead of Revit API to build a universal data component to adopt different BIM packages. The robust network framework to support fast and satisfactory data transmission during emergency situations needs to be further investigated. In addition, an indoor position system (IPS) holds the potential to provide real-time indoor position services during the fire emergency, which might need to be adopted over the current marker positioning system due to the time constraints experienced by the user in a stressful emergency situation (rushing for their life). In addition, the end-users with a disability might need the safest evacuation route rather than the shortest due to their movement limits. Therefore, the specific path finding algorithm for their situation needs to be further developed.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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